

WFO RESOURCE ROOM

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1983 YAMPA RIVER COBBLE REACH
MORPHOLOGY INVESTIGATION

FINAL REPORT

Submitted to:

Endangered Species Office
United States Fish and Wildlife Service
Salt Lake City, Utah

J. S. O'Brien
Civil Engineering Department
Colorado State University

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INTRODUCTION

General

A morphological and hydraulic investigation of the cobble substrate reach of the Yampa River was conducted to determine the natural conditions and processes of the observed spawning habitat of the Colorado squawfish (*Ptychocheilus lucius*). Recent studies, conducted by the U.S. Fish and Wildlife Service (USFWS) and the Colorado Division of Wildlife (CDOW) have concluded that the cobble substrate reach (River Mile 10 to 19) of the Yampa River in Dinosaur National Monument is utilized as spawning habitat for the endangered Colorado squawfish (Tyus et al., 1982, Wich et al., 1983). The morphological investigation of the cobble reach was accomplished concomitantly with the National Park Service (NPS) study, "Hydraulic and Sediment Transport Investigation of the Yampa River." The study team also coordinated efforts to collect field data with the USFWS during 1983 runoff season which was submitted to the USFWS for input to physical habitat simulation computer model (PHABSIM). Results of this study and pertinent information from the NPS study are documented in this report. In the NPS investigation, a computer model was developed to simulate hydraulic and sediment transport conditions for a range of discharges in a portion of the cobble substrate reach. A minimum streamflow hydrograph was designed to preserve the existing cobble substrate conditions. A discussion of that hydrograph and its physical implications is presented herein.

Setting

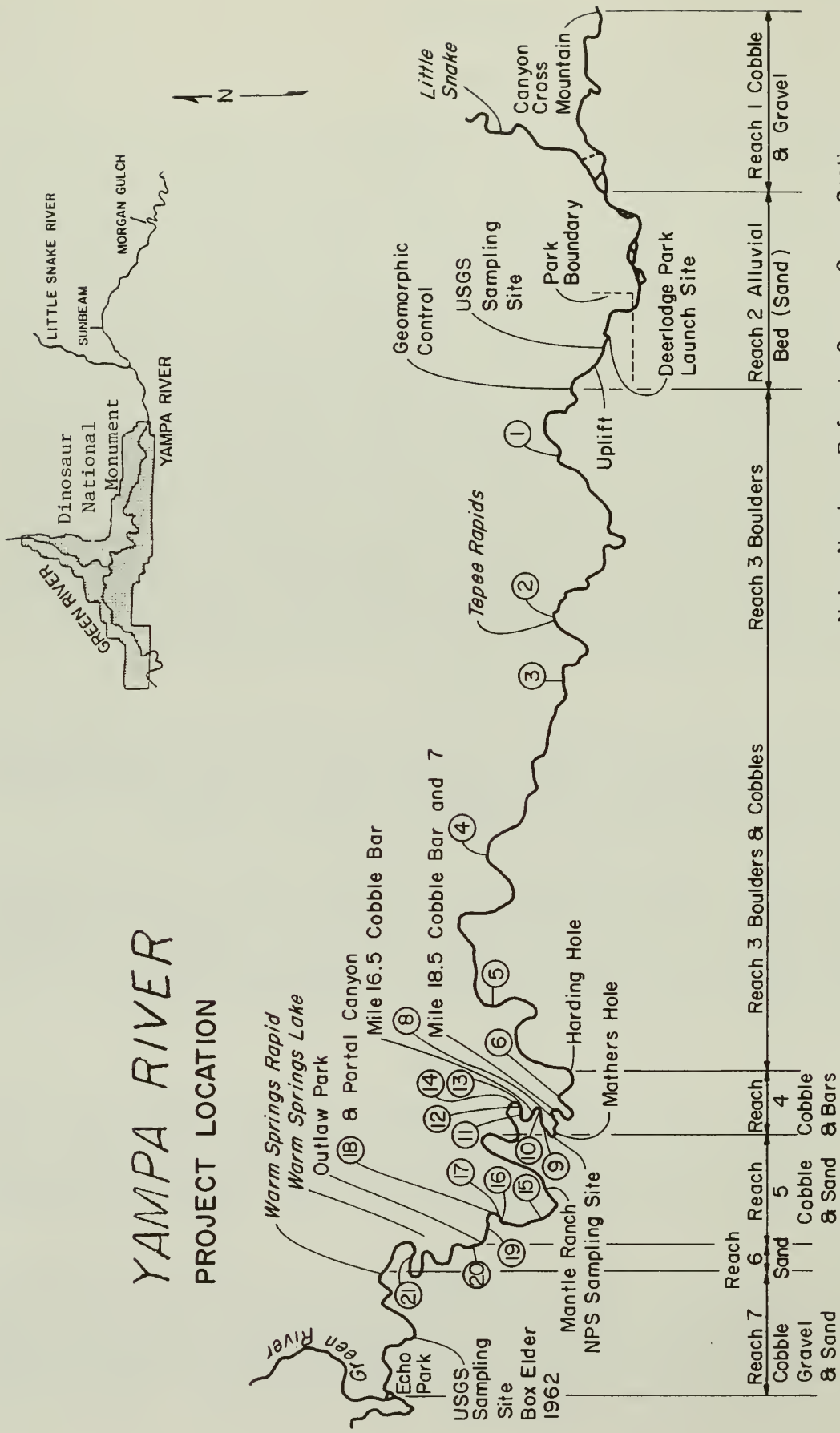
Dinosaur National Monument is in the northwestern and northeastern corners of Colorado and Utah, respectively. It lies between Craig, Colorado and Vernal, Utah. The monument is about 70 miles long (east to west), and ranges from 10 to 25 miles wide (north to south).

The Yampa River headwaters in the White National Forest on the western slope of the Rocky Mountains. It flows north, then west joining the Green River in Dinosaur National Monument (see Figure 1). Draining approximately 7600 square miles before entering the Monument, the Yampa is the Green River's largest tributary. The Yampa River is also the last major free flowing tributary of the Colorado River system.

Background

Dominating the landscape of Dinosaur National Monument are the Green and Yampa River canyons. Both rivers have been entrenching into bedrock since late Cretaceous time, about 70 million years (m.y.) ago. Prior to that time they were meandering rivers flowing on a mature plateau. The rivers still meander, but have incised within steep-walled canyons.

The mechanics of meander entrenchment are not completely understood, but W. R. Hansen has a good theory for incisement of the Green River (1969, and personal communication, 10/7/83). He postulates that the Lower Green originally flowed from Browns Park into the North Platte River on the then-developing Browns Park Formation. Sediments and



Note: Numbers Refer to Canyon Cross-Sections

Figure 1

volcanic ash were accumulating to a thickness of over 7,000 feet. Between the Uinta and Yampa Faults, the eastern part of the Uinta Mountains was collapsing. The Browns Park Formation overtopped the valley rim, and the Green River breached the Uinta crest at the present site of Lodore Canyon. The river cut quickly through the soft Browns Park formation to harder rocks below. The main Green River was still flowing eastward across the rising Continental Divide. The Lower Green incised itself to its new base level, and eventually captured the main Green and turned it south. The Yampa River appears to have a similar history of incision into the Browns Park formation.

The Yampa canyon profile varies distinctly between reaches with different rock lithologies. Two formations are seen most often in the canyon, the Morgan and the Weber. The Morgan consists mainly of limestone beds and underlies the Weber. The Weber is a relatively soft sandstone.

Where the Yampa flows through the Morgan, the valley profile tends to be asymmetrical. On the south side, steep walls are found while the north side slopes gently and is covered with talus. The asymmetry is caused by lithology and the dip of the beds which is 7 to 10 degrees to the southwest. The lower member of the Morgan is an incompetent shale, which rests on the Round Valley Formation, a limestone. Where exposed by the river the shale slides on the Round Valley downslope, causing overlying rocks to collapse. Most landslides therefore occur on north slopes, in the Morgan. The river channel is confined between the steep talus slopes and has no floodplain. Channel location in the valley has been dictated in some reaches by the ancient landslides.

In the Weber formation the canyon's profile is symmetrical. The Weber is a soft sandstone which is easily eroded by the river. Smooth, curving walls are often vertical or past vertical depending on the length of time they are subjected to the erosive forces of the river.

Channel bed slope varies with rock type encountered. In the upper reach of the canyon, the slope is steep where the river flows through the Morgan. Boulders and talus from slides armor the river bed slowing its rate of downcutting through the hard limestone formation. The slope is steeper than in the reach where the softer Weber Sandstone is the controlling formation. Here the river often directly attacks the bedrock, which it erodes easily. The rate of downcutting in the Weber decreases as the channel elevation approaches the Green River base level (Figure 2).

An average 1.5 million acre feet of water flow through the Monument each year in the Yampa, contributing on the average 1.5 to 2.0 million tons of sediment per year. Almost all of the sand sediment load is delivered by the Little Snake River entering the Yampa just four miles east of the Monument Boundary. This sediment load is transported through the cobble substrate reaches in the lower half of the canyon.

Three study sites were selected in the cobble bed reach of the Yampa River. River mile 16.5 and 18.5 were chosen for hydraulic investigation of the cobble substrate. Hydraulic and sediment transport data were collected at the Mathers Hole site located between the other study sites. A description of the sites follows.

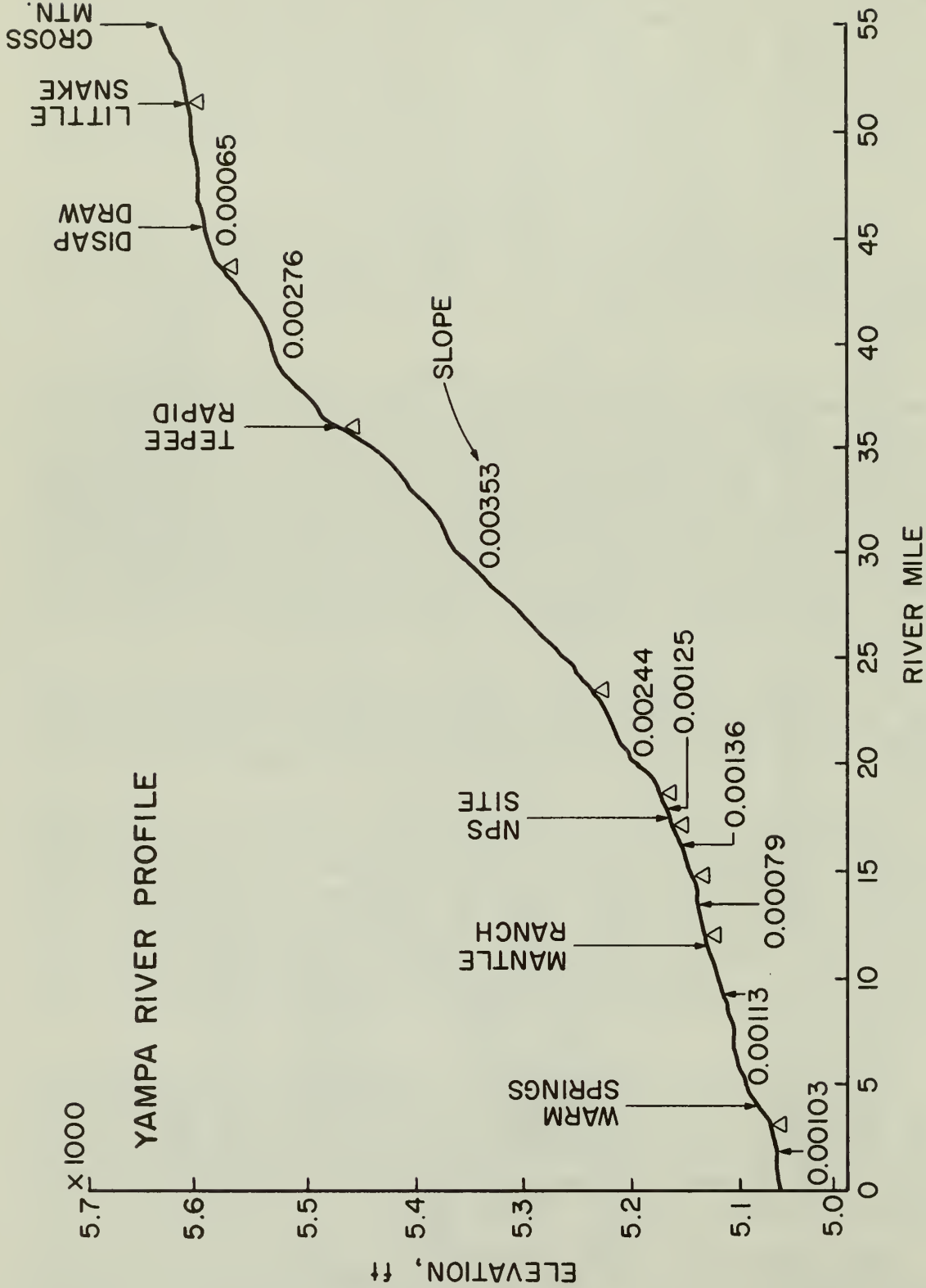


Figure 2

River Mile 16.5

The cobble bar at river mile 16.5 is a large cobble and sand longitudinal bar (approx. 900 ft. long and 300 ft. wide). It splits the main channel into two smaller channels (or three at high flows—see Figure 3). The Weber Sandstone is exposed through the entire cobble bar reach, attaining a maximum thickness of about 700 feet on the left bank. Talus and soil is found at wall bases and supports grasses, junipers, and box elders. The Weber is a tan to buff colored, very fine grained to fine grained, manganese and iron-oxide stained quartz arenite (90 to 100% quartz) with occasional mud clasts, of Pennsylvanian age. The dominant primary structures are trough cross-beds and planar cross-bed sets, with large foreset beds occasionally seen. Coatings of calcite and some vuggy calcite are present. The unit was deposited in a near-shore/beach area, both subaerially (dunes) and in shallow marine waters. The formation also contains some limestone (Hansen, 1969). It is poorly consolidated and thus easily eroded, forming steep, smooth, curving walls. On the left bank is a vegetated floodplain which extends to the midpoint of the cobble island, where it meets Weber talus and some sand.

Appearing below cross-section 4 (Figure 3), on the right bank, is a limestone bed in the Morgan Formation (lower Pennsylvanian). It dips upstream at about 6°, rises through the remainder of the section, and is about 10 feet thick. The outcrop does not become prominent until about 80 feet above cross-section 2. The limestone is reddish-rust brown on weathered surfaces, gray-brown on fresh surfaces, very fine crystalline to medium crystalline, is irregularly fractured, solution-pitted, and forms jagged, angular outcrops. This outcrop is far more erosion-resistant than the Weber Sandstone, and extends into the channel rather than being sharply cut off. Here it accumulates muds and supports algae. On the left bank only a small portion of the limestone is seen, just above cross-section 1, but it quickly disappears under talus.

The bed material is essentially cobbles from cross-section 1 to 5, with exception of the large pool in the left channel near cross-section 2 which consists of sand and boulders and a large portion of the right channel which is small boulders from the talus slope. Cross-sections 6 through 8 constitute a pool reach with a large percent of the substrate being sand. The pool is at cross-section 7 is deep with large submerged boulders. The riffle extends from cross-section 5 to cross-section 1 and includes both channels.

River Mile 18.5

At river mile 18.5 is another cobble, riffle reach which is similar to that at mile 16.5. A longitudinal bar of cobbles and sand splits the main channel into two subordinate channels (Figure 4). The Weber Sandstone is exposed through this reach with no trace of the Morgan Formation. As with the site at mile 16.5, an overhanging ledge is found at mile 18.5. It rises from the water about 50 feet below the uppermost point of the bar, and continues to rise throughout the remainder of the

YAMPA RIVER SPAWNING REACH RIVER MILE 16.5 AT 1000 CFS
ON AUG. 11, 1983

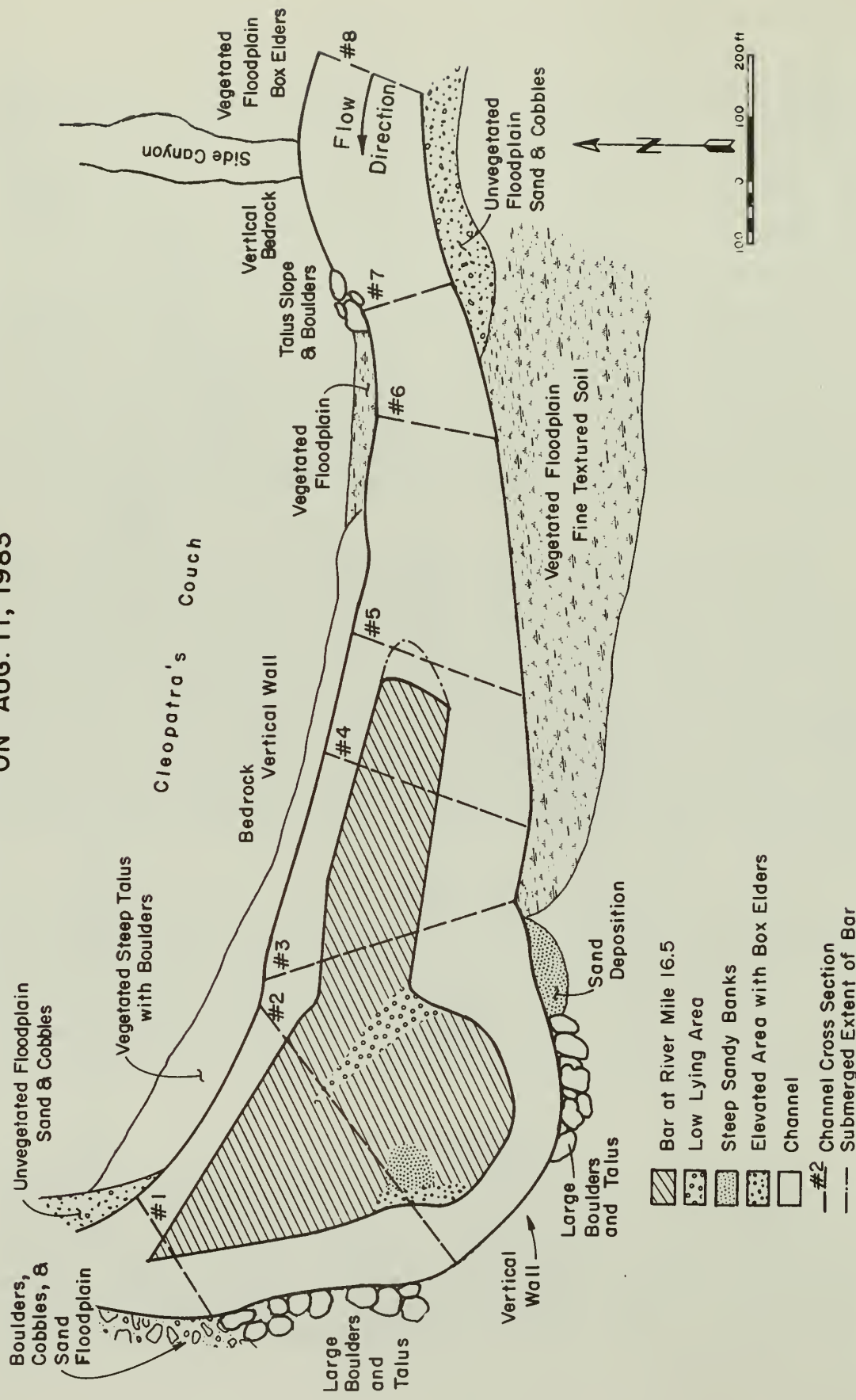


Figure 3

YAMPA RIVER SPAWNING REACH RIVER MILE 18.5 AT 500 CFS ON SEPT. 13, 1983

- Channel

#3

—

Cross Section

— · —

Submerged Extent of Bar

Unvegetated Cobbles

Unvegetated Sand

Unvegetated Sand and Cobbles

Vegetated Sandy Soil

Vertical Sandstone Wall

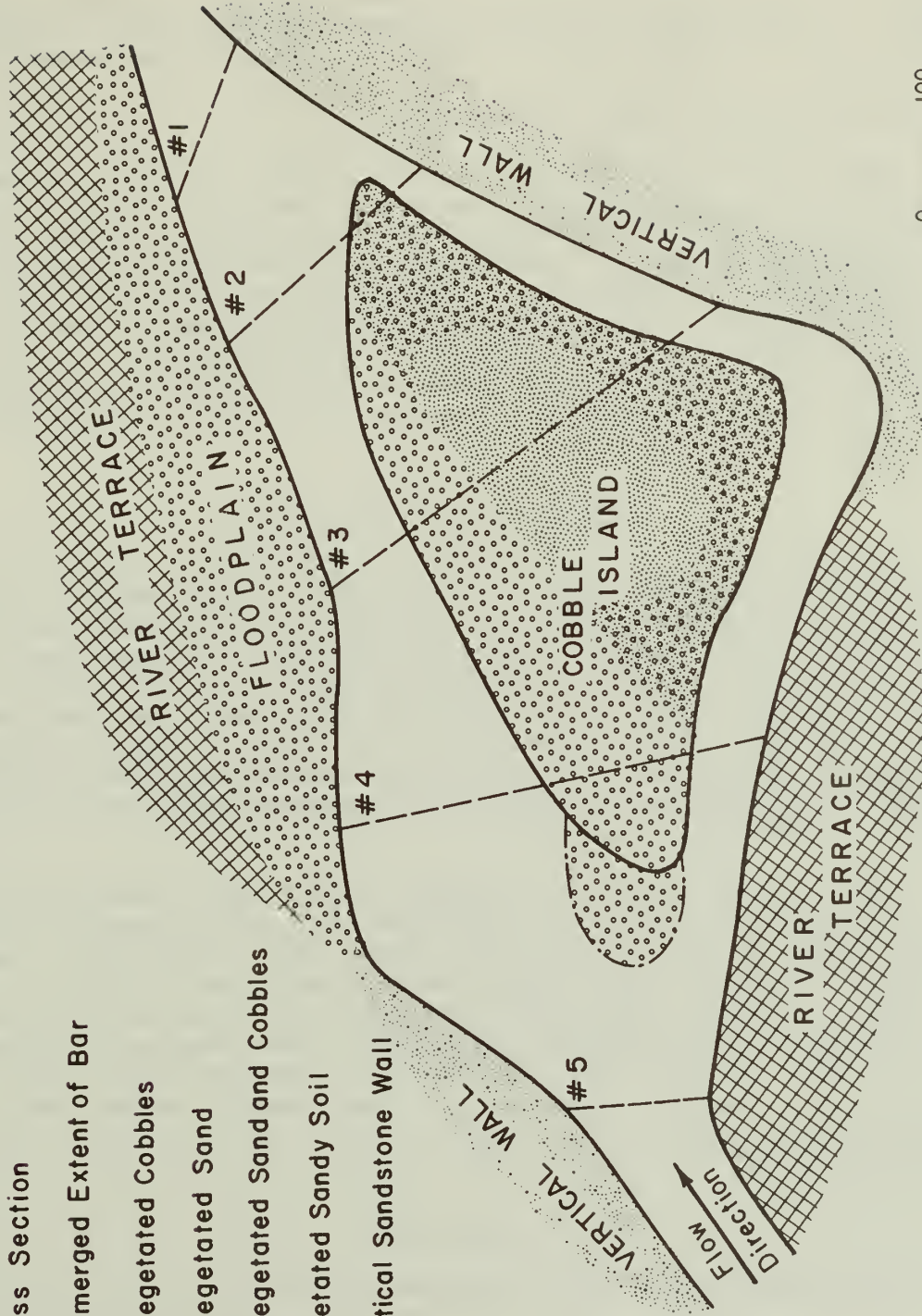


Figure 4

stretch. Instead of limestone, however, the rock is Weber Sandstone, which is easily eroded. Water diverted around the cobble bar flows with against this outcrop and has formed an overhang of about 25 feet. On the underside of the ledge moss grows, and is fairly thick and lush near the water surface at the upstream end.

Most of the river flow passes through the left channel thalweg. At high flow the cobble island is completely submerged. Cross-section 5 is a deep pool with a sand substrate. The riffle initiates at cross-section 4 and extends to cross-section 2. Cobble substrate is found in both channels in the riffle with large cobbles and small boulders comprising the bed material in the left channel near cross-section 3. Both the cobble bars at river mile 16.5 and 18.5 are constructed of cobbles deposited in a flow expansion. The cobble bar at river mile 18.5 has considerably more sand covering the cobbles when exposed at low flow than at river mile 16.5.

Mathers Hole, River Mile 17.5

Mathers Hole is located between the two previously described sites. It was established in a pool reach of the river, which is partially armored with cobble substrate. Cobble bars or islands are located immediately upstream and downstream, dividing the flow and creating riffles where it is constricted between the islands and bedrock walls. This recurring riffle-pool sequence constitutes a reach of the Yampa River from river mile (RM) 16.5 to 20.5. Cobble bars or islands have developed just upstream of each incised meander bend where the channel widens. The river is described as a wide bend, point bar stream with a distinct riffle-pool sequence.

The site is reasonably straight with a short longitudinal cobble bar that becomes exposed at low flows. The left bank is a vertical Weber Sandstone wall, six hundred feet high. The right bank is a vegetated terrace rising approximately twelve feet above the cobble substrate. The river has entrenched a channel below this bench which is very stable up to bankfull discharge. The thalweg is permanently located near the left bank. During peak flows the water surface slope is uniform for several river widths downstream. A riffle-pool sequence develops with dropping stage and the water surface slope through the site is reduced.

Objectives

The objectives of this investigation are:

- 1) Collect field data to predict, through the application of the PHABSIM computer model, the habitat availability—flow relationship that exists for spawning and adult lifestages of the Colorado squawfish at RM 16.5 and a replicate site RM 18.5.

- 2) Describe the channel morphology of the cobble substrate reach in the lower Yampa River.

- 3) Relate hydraulic and sediment transport data collected at other sites in the canyon with conditions observed at the RM 16.5 site.

4) Determine the range of discharges required to preserve the morphological conditions that have been observed or projected to have existed during the 1981-1983 squawfish spawning periods.

Additionally, a physical model study was conducted to define the phenomena of sand transport over cobble substrate. This flume investigation was also designed to calibrate the Helley-Smith sampler.

This entire investigation was conducted concurrently with the NPS hydraulic and sediment transport study whose overall objective was to quantify a minimum streamflow hydrograph, based on an understanding of hydraulic and sediment transport phenomena, that will preserve and maintain, on an annual basis, a range of natural conditions and processes vital to the biological system of the Yampa River in Dinosaur National Monument.

METHODS

Field Data Collection Program

At river mile 16.5, eight cross sections were established for hydraulic data collection. Similarly, five cross sections were selected at a second site, RM 18.5. Water surface slope, velocity, depth and substrate data were collected at both sites. One set of data at each cross section was obtained in April, three additional sets were taken in July and August at RM 16.5. At RM 18.5, the cross sections were monitored three times during the recessional limb, just one or two days prior to the measurements at RM 16.5. This data was reduced and prepared for input to the PHABSIM habitat simulated computer model.

Cross section profiles were plotted with a sonar depth chart recorder. These profiles were monitored at ten foot stations across the channel width and were calibrated by surveying the end points. Water surface slopes and cross section reference points were surveyed. The slope was determined by surveying the distance between the cross sections on each bank and recording the water surface elevation. The slopes were also measured, at other incidental sites, several river widths upstream and downstream.

Velocity was measured with the Price current meter or the Price pygmy meter in all facets of the project. The average velocity for each ten foot cell was taken at the 0.6 depth below the water surface. Several vertical velocity distributions were plotted to check the reliability of 0.6 depth measurement. In several instances velocity measurements were taken at 0.2 and 0.8 depth interval to improve the accuracy of the measurements.

Sediment discharge measurements were collected at the Mathers Hole site. These measurements constitute the sediment supply to the cobble bar reach of river mile 16.5. Data collection for 1983 was greatly expanded over the previous year's program. Forty-three daily sets of sediment data were collected, with the highest sampling discharge being 19,300 cfs. Measurements were made on both the rising and recessional

limbs; 28 sets of sediment data were collected on the rising limb and 15 sets on the falling limb. The sediment samples were supplemented with measurements of water surface slope, river width, cross section profiles and velocity.

Suspended sediment samples were collected at ten foot verticals with a U.S. Geological Survey (USGS) D-74 depth integrating, suspended sediment sampler using the ETR (Equal Transit Rate) method. The Helley-Smith sampler was employed to collect unmeasured sediment zone samples near the bed. It was operated at each vertical in conjunction with the D-74 sampler. The Helley-Smith is not a sanctioned sampler by the USGS but represents the best available technology for bedload and unmeasured suspended zone sampling. Of the forty-three sets of sediment samples, forty-two Helley-Smith samples and thirty-nine sets of suspended sediment were collected.

Discharge measurements were facilitated in 1983 by erecting a staff gage. A stage-discharge relationship was calibrated with 24 measurements over the two field seasons. The Mathers Hole cross section becomes a more effective conveyor of discharge at higher stages which results in the nonlinear stage-discharge relationship shown in Figure 5. Discharge was measured from 600 cfs to 19,000 cfs to define the relationship.

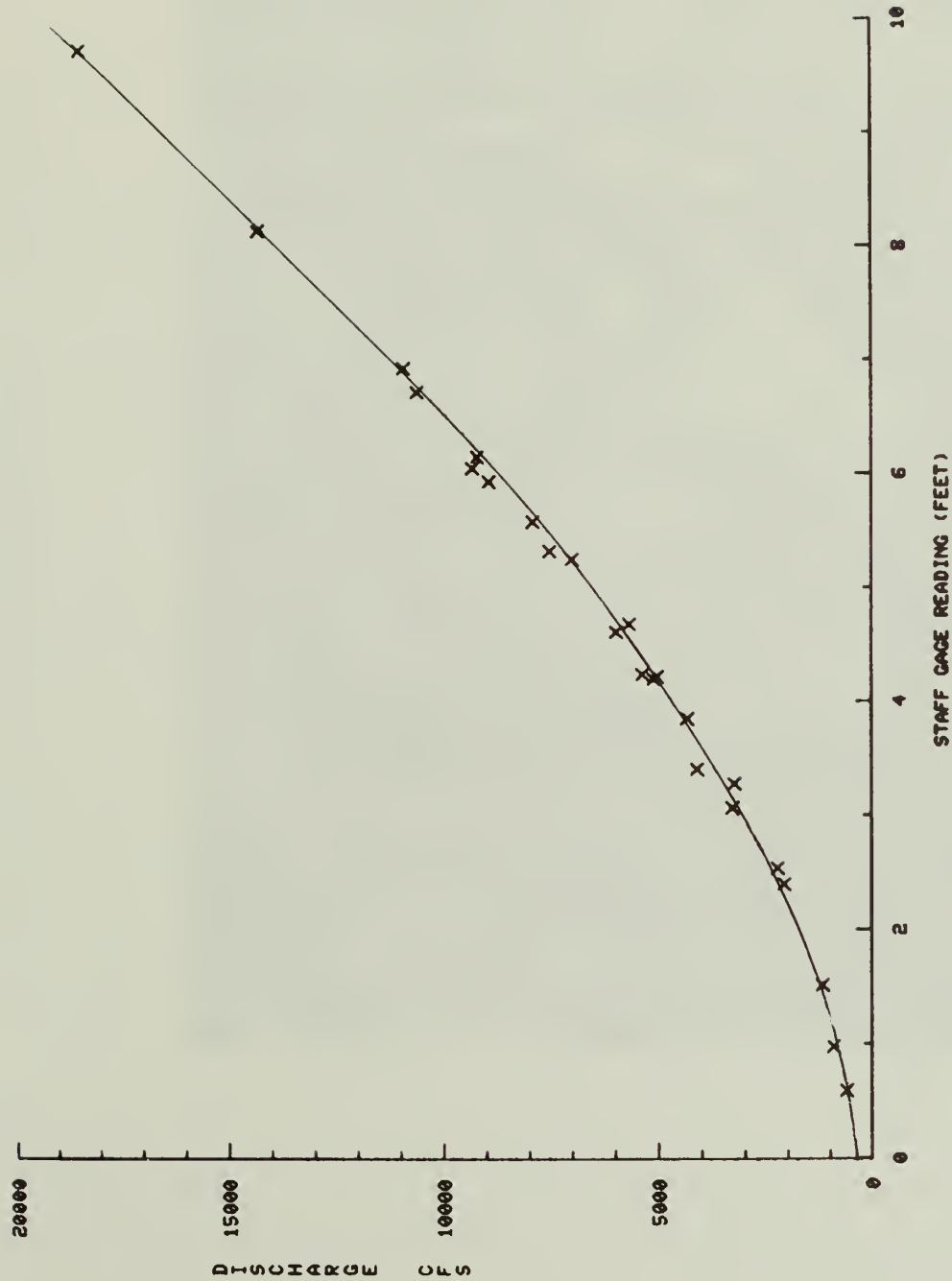
Substrate analysis was accomplished with a probe. The composition was verified at low flow by observation of the exposed channel and by walking the cross section at shallow depths. Numerous photographic analyses were made with calibrated square. These photographs were evaluated with collected surface and subsurface substrate samples at several cross sections on the spawning bar (Photo 1).

The velocity, depth, slope and substrate data was reduced and presented to the USFWS for input to PHABSIM computer model. All the data was prepared in standard forms and the cross section profiles were all referenced to a single point assigned the arbitrary elevation value of 100 feet. This data constitutes the subreach data base for eight of the eleven cross sections used in the water and sediment routing model.

RESULTS AND DISCUSSION

Yampa River Canyon Morphology

The Yampa River canyon incised meanders are the dominant physical feature in the plateau topography. This unique physical environment creates a diverse biological habitat. Complex relationships exist between the aquatic species and the habitat created by the river. Response of the physical system to changes in flow regime would disturb the stable, equilibrium conditions which support the river ecosystem. The channel morphology and aquatic environment is a function of several interrelated physical features of the system including geology, climate, basin size, topography, sediment transport, and others. The following discussion will focus on the important aspects which define the range of natural conditions and processes that exist in critical or sensitive habitat reaches of the Yampa River.



STAGE - DISCHARGE RELATIONSHIP MATHERS HOLE 1982 & 1983

Figure 5



Photo 1. Cobble Substrate at River 16.5

The incised meanders have an average wavelength of approximately 0.62 miles. The original formative discharge for producing the paleochannel meanders with a wavelength of 0.62 miles is approximately 10,500 cfs. This is derived from empirical relationships of existing rivers (Richards, 1982). The corresponding width is about 250 feet or equal to present day width. Over geologic time the annual discharge has increased. As the base level dropped and the river incised in bedrock, the drainage basin developed increasing the annual discharge.

Every river system evolves in a manner that establishes approximate equilibrium between the channel and the water and sediment it conveys. The reaches in the canyon comprise the profile shown in Figure 2 which reflects the long term evolution on geologic temporal and spacial scales. In the upper reaches of the canyon, the river has incised in the Morgan shale formation. Boulders and talus from steep side slopes comprise most of the bed material. Downcutting is inhibited by the large substrate and the erosion resistant formation.

The slope-substrate-discharge relationship is complicated. Size of the bed material is proportional to the depth and slope and generally, a milder slope will result in a smaller substrate. The downstream decrease in bed material sizes is the result of sorting as a function of slope. Abrasion accounts for some of the downstream size reduction. The river contacts the Weber sandstone in the lower portion of the canyon. In many areas the river flows directly on the sandstone bedrock which is soft and easily eroded. As the Green River confluence approaches the river slope becomes more mild. Reaches of cobble substrate have evolved into a riffle-pool sequence in this section. The very mild sloped portions have a sand and gravel substrate. In contrast, the initial twenty-five miles of canyon, are uniformly steep punctuated by rapids and backwaters formed by side canyon flood events.

The river is characterized in the cobble substrate reach as a wide bend, point bar stream with a distinct riffle-pool sequence. The wider bends are the remnants of the meandering paleochannel whose pattern was partially preserved in the structure of incised bedrock canyon. The Yampa riffle-pool sequence is not typical of a natural meandering river because of the bedrock controls. Riffle spacing is normally five to seven times the channel width, but riffles have developed in the Yampa wherever channel expansions have occurred; most often just upstream of wide bends.

The long term development of the shape, size and orientation of cobble bars and islands in this reach has been a gradual process starting with initial formation of meander incision. Over geologic time a sequence of large, infrequent discharges contribute to the progressive downstream movement of the cobbles. The riffle-pool sequence evolves as a function of the large discharges; the cobbles tending to pile up in the flow expansions upstream of bends. The riffle is initiated by the leading edge of the depositional region. In this fashion, the bar or island stability has been established on a quasi-permanent scale with lesser discharge events inciting limited cobble motion. Without entrainment, cobble movement is limited to short hops, leaps and rolls, and the effect on the bar shape is negligible.

The dynamics of the system involving the replacement of cobbles as they are plucked away in short sprints is the genesis of a clean substrate. Cobble motion is initiated on differential basis, the smaller sizes moving first until at extreme flows, all except the very largest sizes may move. Historical tracking of a given cobble would reveal a slow, tedious progression of the cobbles over the bar with the movement consisting of short hops and jumps. Cobbles entrained in the flow on a riffle, however, will probably be carried through the pool to the next riffle with eventual deposition on the upstream adverse slope. Pool constrictions experience greater incremental increases in depth and velocity which will insure cobble motion to the next riffle. When relatively large cobbles have deposited in a riffle, the propensity for other particles to join increases.

Maintenance of dynamic equilibrium requires progressive adjustment of slope and spatial variation. Bars tend to be energy dissipating structures that promote overall channel stability. Energy expenditure per unit bed area is equalized with mobilization of cobbles and localized width and depth adjustment. Channels around cobbles bars are reformed with failing side slopes and changing widths. At peak flows vertical accretion of the cobble bar is an example of depth adjustment. Such accretion, forces additional flow to impinge on the banks and create side channels of high velocity and unstable beds.

Historical Flow and Flood Frequency Analysis

USGS gaging stations are located at Maybell on the Yampa River and Lilly on the Little Snake, approximately 40 and 15 miles upstream of Dinosaur National Monument, respectively. No substantial tributary inflow or stream losses occur in the intervening reach and therefore, the gaging station flows represent the inflow to the Monument. On the average, the USGS discharge computed by combining the discharge at the stations is slightly higher than that discharge measured at Mathers Hole (see Figure 6). This comparison is only relative, however, being a function of the flow travel time, the time of day that the discharge measurements are made and the magnitude of the unsteadiness of the flow. The average difference of 6.5% (absolute) between the discharges gives credibility to stage-discharge relationship at Mathers Hole.

The 1983 Yampa River discharge and the mean annual discharge are shown in Figures 7 and 8. The mean annual discharge was calculated using the period 1941-83. The period from 1922-83 constitutes the entire period of record. The first 20 years of this record were wetter than the remaining 40, and the 1941-83 period is more representative of the conditions that exist today in the Yampa River (USGS, John Elliott, personal communication, 2/83). Table I reveals the marked difference between the periods. The lower discharge period, 1941-1983, has a mean water yield of 1,483,700 acre-feet, compared to 1,508,400 acre-feet for the entire period of record.

Figures 9 and 10 are plots of the five and ten year running average of the annual volumes of the Yampa River at Deerlodge. The climate was drier than normal from about 1935 through 1965. The 1920's and 1965-1975 are wet periods which offset the dry period in the 1930's and 40's.

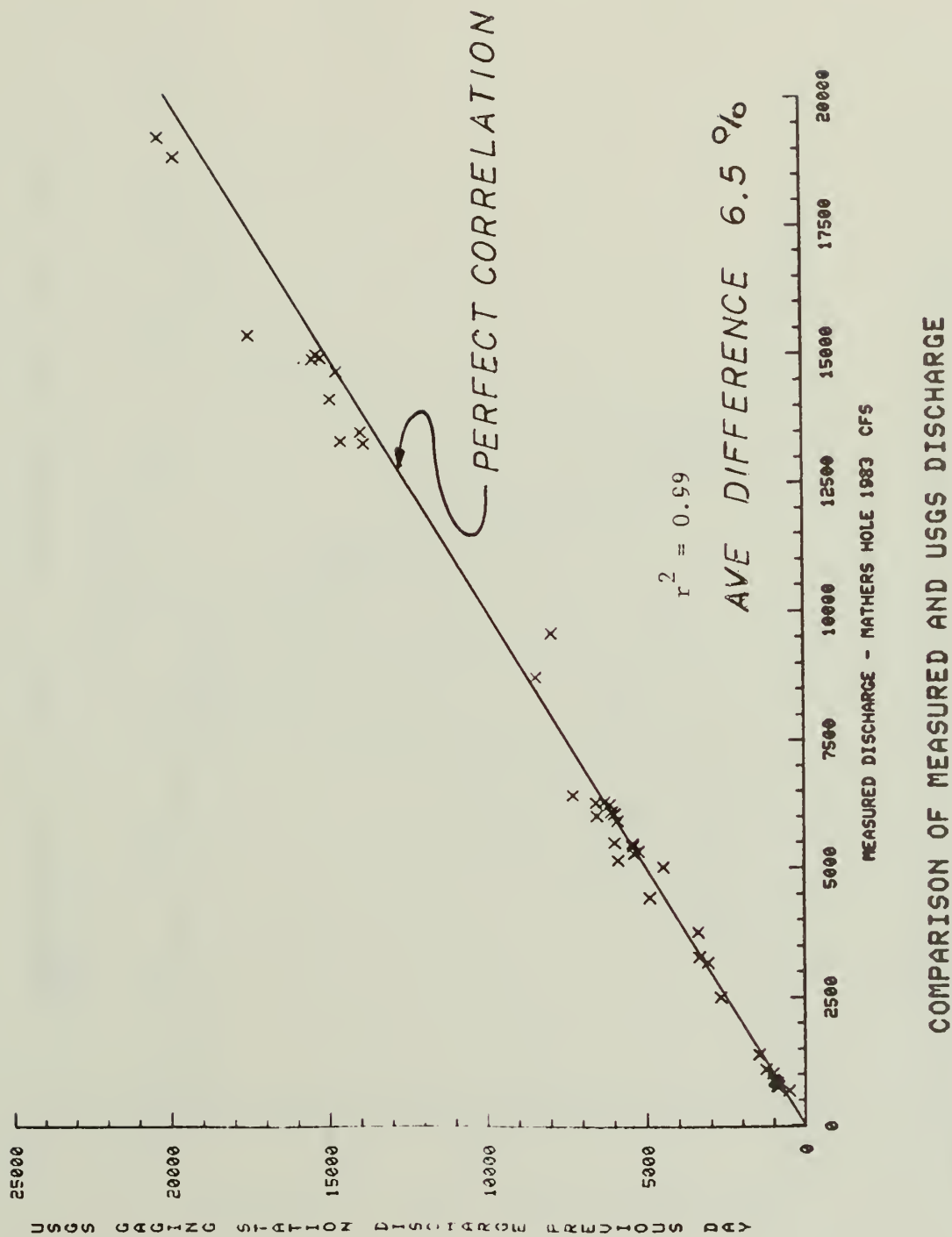
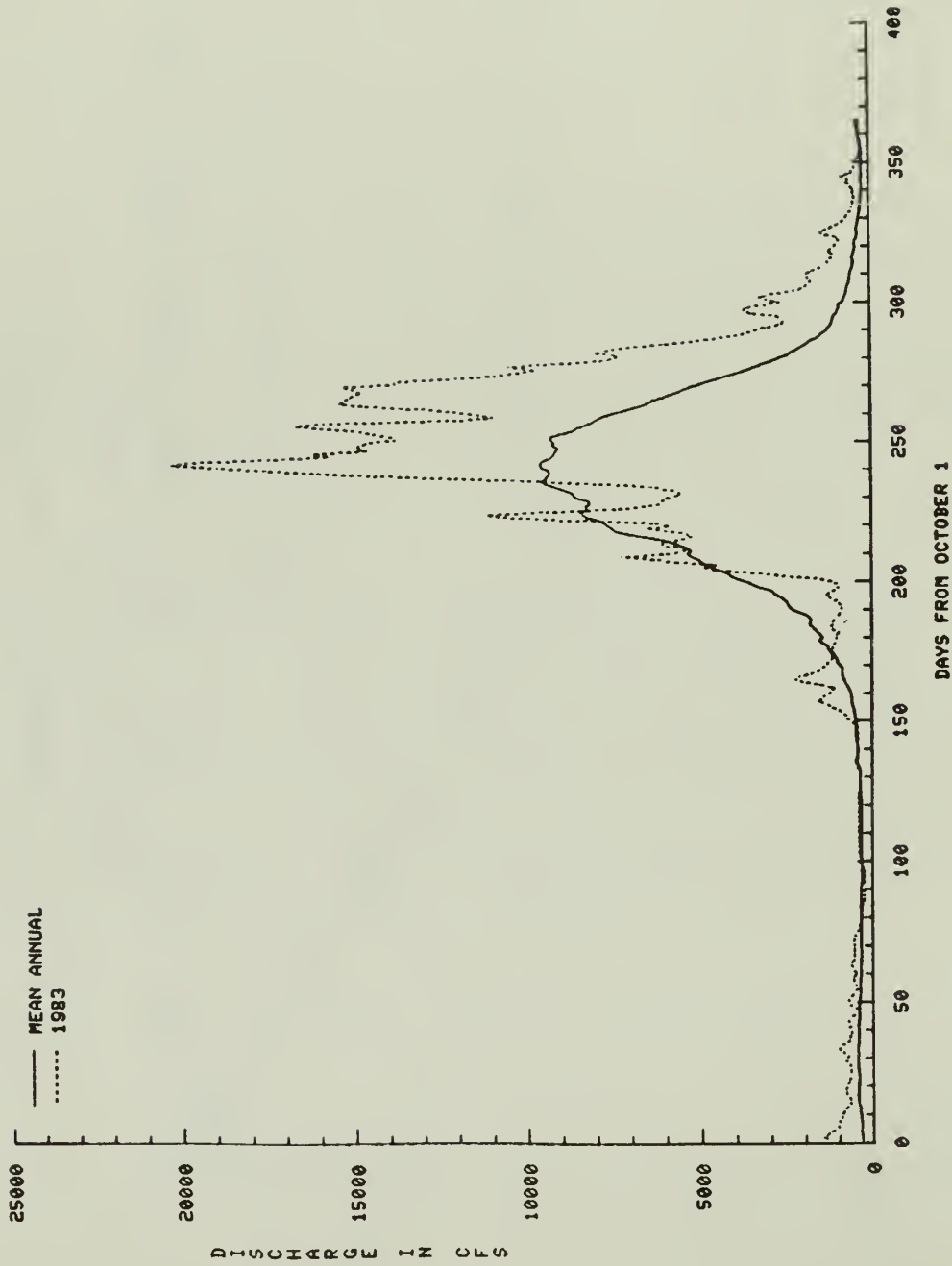
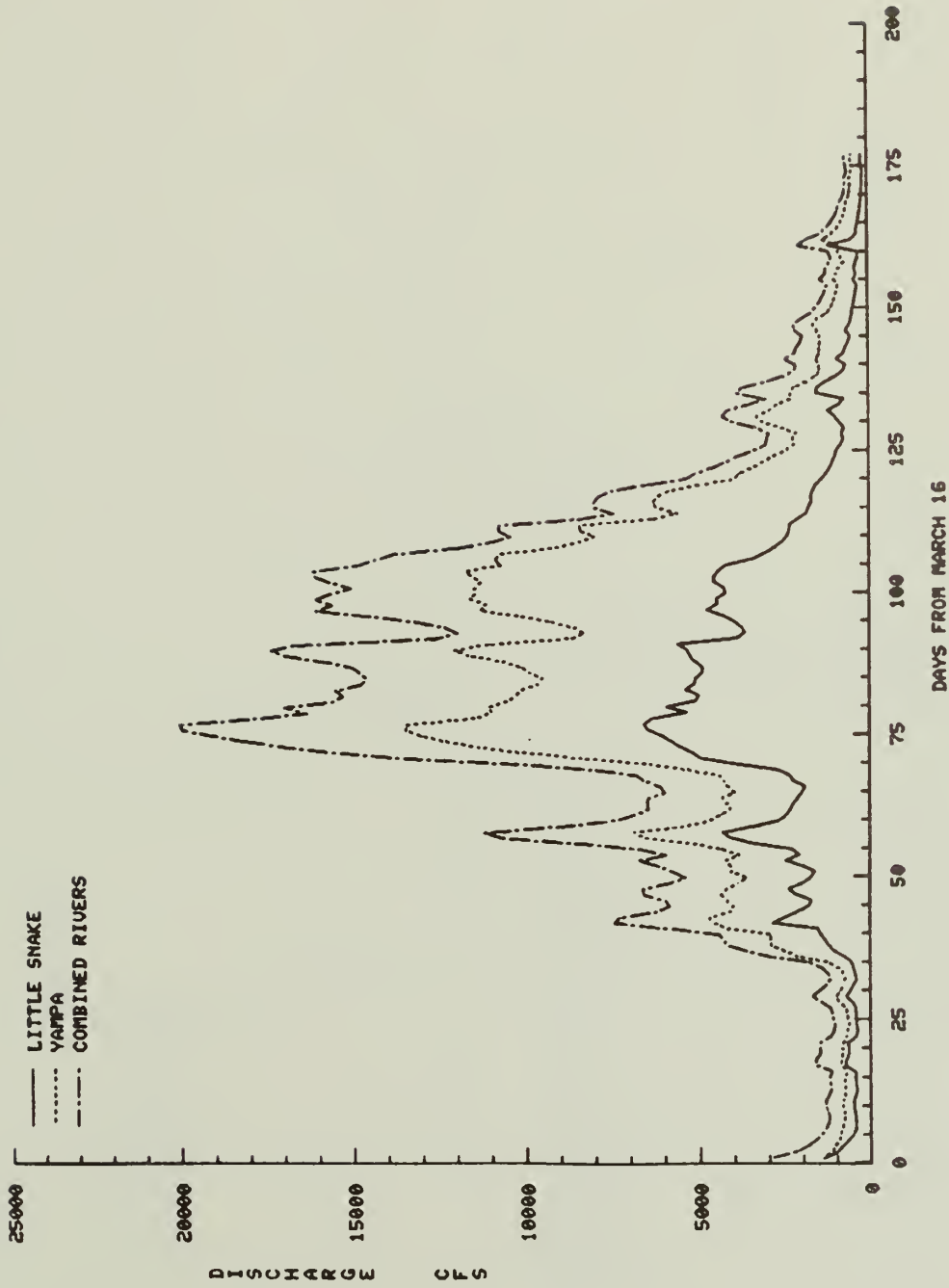


Figure 6



YAMPA RIVER DISCHARGE - DEERLODGE PARK, 1983 & MEAN

Figure 7



YAMPA - LITTLE SNAKE RIVERS HYDROGRAPHS 1983

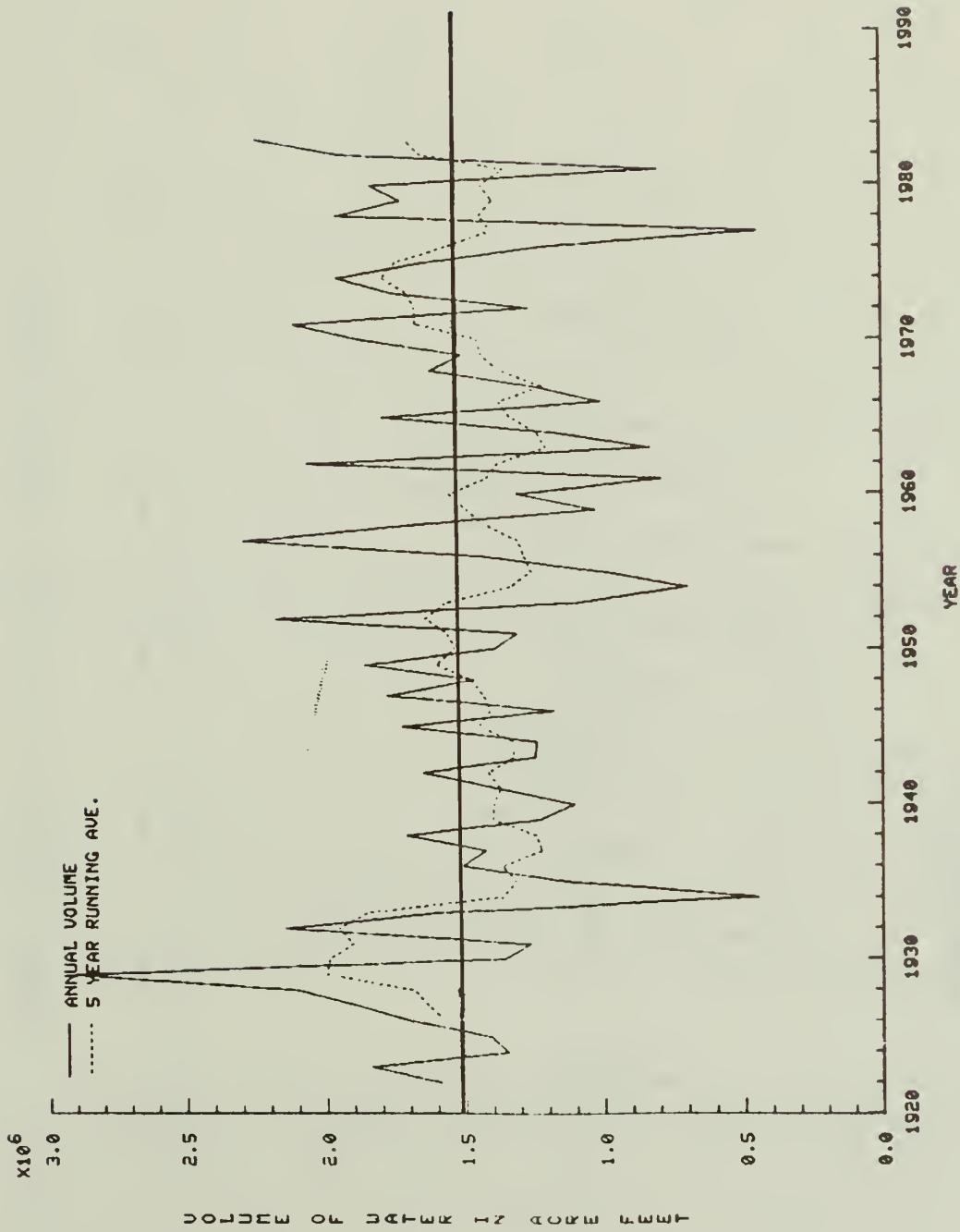
Figure 8

Table I. Historical Flow at Deerlodge Park

Period	Mean Annual Discharge (cfs)	Mean Annual Flow (acre-feet)	Base Flow Sept 1 - Feb 28 (cfs)	Mean Annual Peak (cfs)
1922-38	2,221	1,609,100	435	11,391 (May 28)
1941-83	2,048	1,483,700	367	9,597 (May 30)
1922-83	2,082	1,508,400	384	9,892 (May 29)

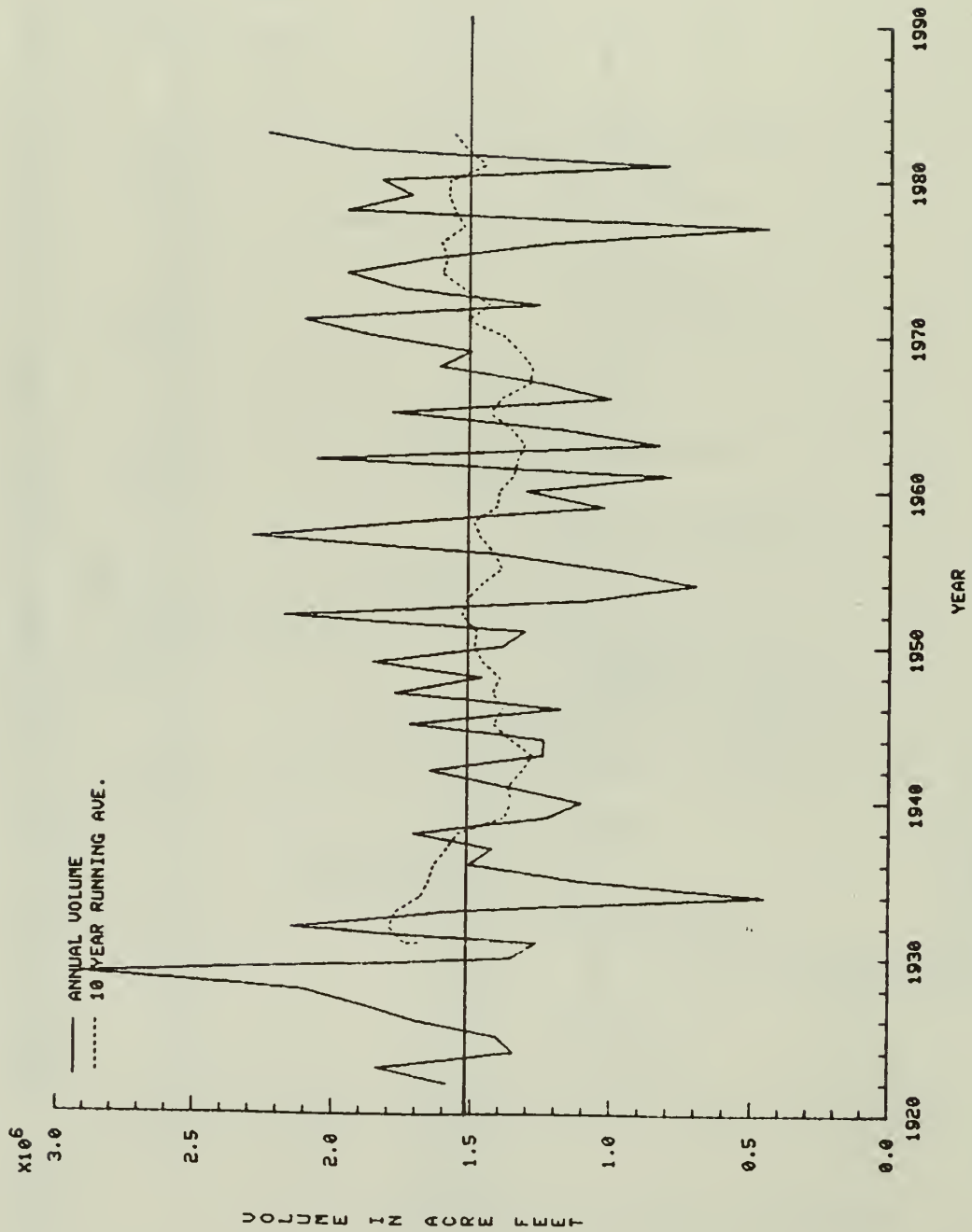
Table II. Flood Frequency Analysis

Return Period (years)	Discharge (cfs)	
	Gumbel	log-Pearson type III
1.01	12,000	
1.05	12,120	
1.10	12,270	
1.25	12,690	
1.5	13,280	
2	14,220	14,070
5	17,200	17,710
10	19,460	19,270
20	21,720	20,170
25	22,450	20,630
50	24,700	21,340
100	26,960	21,850
200	29,220	22,240
500	32,200	
1000	34,460	23,240



YAMPA RIVER ANNUAL DISCHARGE VOLUMES AND 5 YEAR RUNNING AVE.

Figure 9



ANNUAL VOLUME AND TEN YEAR RUNNING AVERAGE

Figure 10

The period of record is too short to discern any distinct cycles. The sediment record for the Little Snake, however, occurs during a drier than average period. It is difficult to speculate on the relative magnitude of sediment yield during dry or wet periods but generally, in semiarid regions, a decrease in runoff retards erosion.

Instantaneous peak discharges are generally used to estimate discharge frequency. Since the flows from the two gaging stations are combined to determine the daily discharge at Deerlodge Park, the use of instantaneous peak discharges is inappropriate. Discharges of a specified return period are determined by the application of a theoretical probability distribution. Richards (1982) reports that the Gumbel Extreme Value distribution is a model which generates a linear function on a transformed probability scale. It is a two parameter model which seems to yield more representative values for the Yampa River than the log-Pearson type III model. The results of the Gumbel distribution and log-Pearson type III are shown in Table II. The Gumbel distribution is plotted in Figure 11. The 1983 peak discharge of 20,300 cfs has a return period of approximately 13 years based on the Gumbel analysis and over 20 years based on the log-Pearson type III. Four discharges in 62 years have exceeded 20,000 cfs which is a return period of about 15 years. The maximum recorded peak discharge was 21,750 cfs in 1974 (see Table III). The one hundred year event is about 27,000 (Gumbel) and 22,000 cfs (Pearson). The bankfull discharge return period is about 16 years based on the Gumbel distribution.

The 1983 Yampa River hydrograph in the Monument had the fourth highest peak discharge and the third largest annual volume in the 62 years of historical record. These values are 6.7% and 22.6% smaller than the maximum historical discharge and volume respectively.

Effective Discharge and Bankfull Discharge

Effective discharge is the flow that transports the most sediment over a long period of time. It is the product of the magnitude of the sediment transported by a given discharge and the frequency of occurrence of that discharge. The effective discharge is approximately 11,500 cfs as shown in Figure 12. The return period for this discharge is about 1.5 years (Table II). From the stage-discharge relationships and survey measurements at Mathers Hole, the bankfull discharge was calculated to be approximately 21,500 cfs, which has return period of about 20 years.

Bankfull discharge is usually afforded the status of a "dominant" discharge event which controls channel morphology. It is responsible for creating the channel morphological characteristics, changing width/depth ratios, forming or destroying bars and islands, and changing bends and meanders. For alluvial streams this is often an intermediate magnitude flow with a return period of 1.5-2.0 years (Rosgen, 1982). Such a discharge is sufficiently frequent to be an effective channel-forming event. Large floods are too infrequent to control channel morphology. The Yampa River, however, is not alluvial stream in the canyon, but an incised river with an armored bed whose channel adjustment flows are limited to infrequent events.

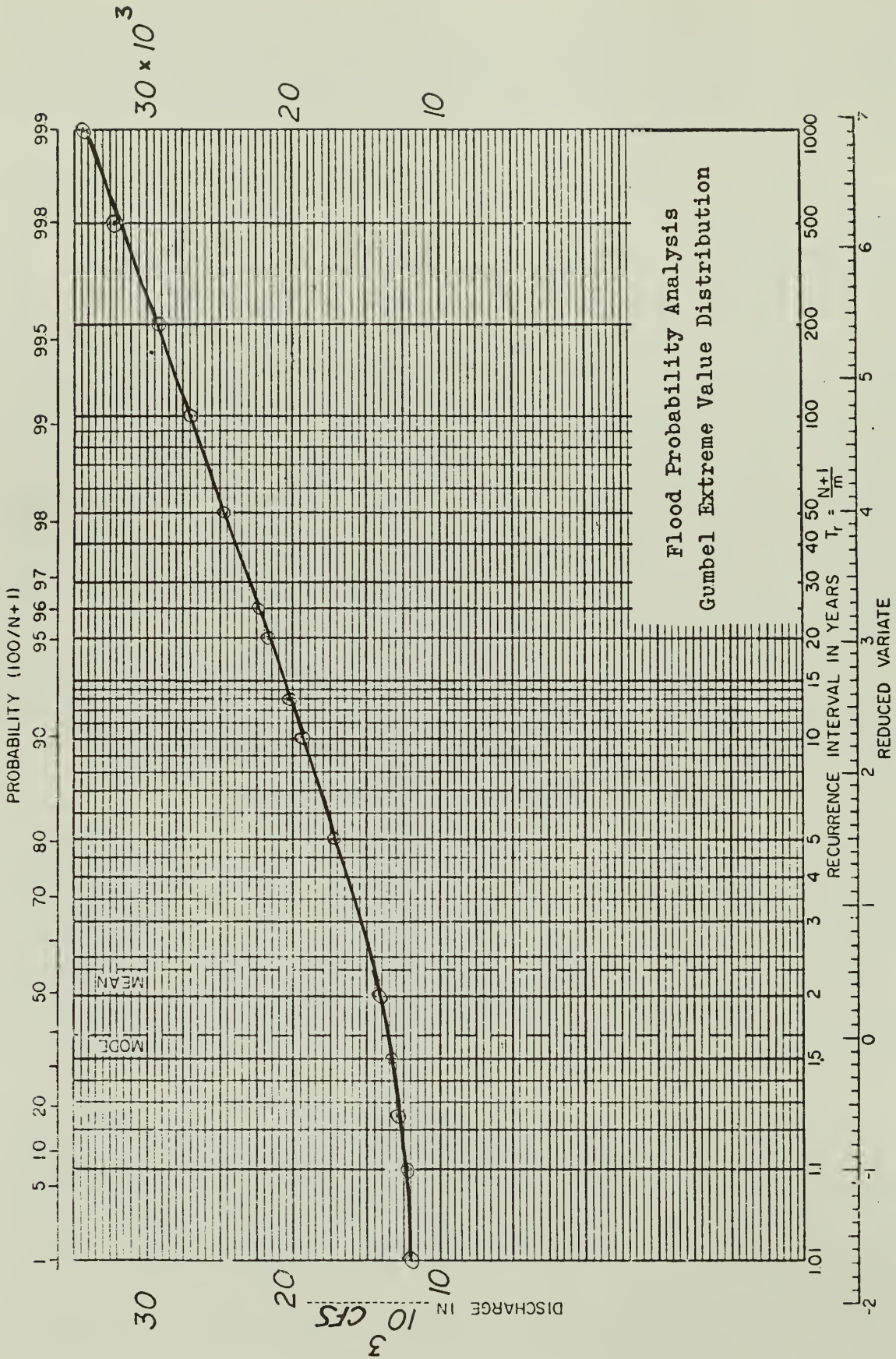


Figure 11

Table III. Historical Peak Flow and Annual Volume

Rank	Year	Flow (cfs)	Volume (acre-feet)
1	1974	21750	1956125
2	1929	21680	2902553
3	1957	20520	2289240
4	1983	20300	2246512
5	1952	19920	2175005
6	1928	18990	2106429
7	1938	18950	1708732
8	1932	18800	2144967
9	1970	18420	1869818
10	1979	18120	1727802
11	1971	17900	2112790
12	1973	17270	1751740
13	1947	17080	1777476
14	1980	17030	1835731
15	1958	16740	1693288
16	1927	16730	1887604
17	1943	16330	1244955
18	1975	16320	1639329
19	1926	16160	1691386
20	1922	16150	1584567
21	1978	16150	1958202
22	1962	15790	2060738
23	1945	15750	1722819
24	1968	15750	1622582
25	1923	15500	1838252
26	1965	15440	1793325
27	1941	15350	1384672
28	1933	15090	1599209
29	1982	15070	1943124
30	1942	14920	1649526
31	1948	14910	1466055
32	1937	14740	1426433
33	1936	14490	1508971
34	1964	14210	1184427
35	1944	14120	1241415
36	1949	13350	1857943
37	1956	12920	1443543
38	1953	12440	1097929
39	1950	12300	1393951
40	1967	12030	1253888
41	1935	11970	1120021
42	1940	11950	1106580
43	1951	11540	1310703
44	1972	11090	1266828
45	1969	10980	1508031
46	1939	10850	1233386
47	1976	10790	1207034
48	1960	10600	1310152
49	1924	10570	1347465
50	1930	10080	1359346

Table III. Continued.

Rank	Year	Flow (cfs)	Volume (acre-feet)
51	1946	9830	1179419
52	1931	8890	1265287
53	1955	8850	1005751
54	1981	8650	802459
55	1925	8590	1408446
56	1966	8330	1008993
57	1963	8250	833860
58	1959	8220	1029978
59	1961	7680	792112
60	1954	6780	700438
61	1934	4402	454095
62	1977	3821	448427

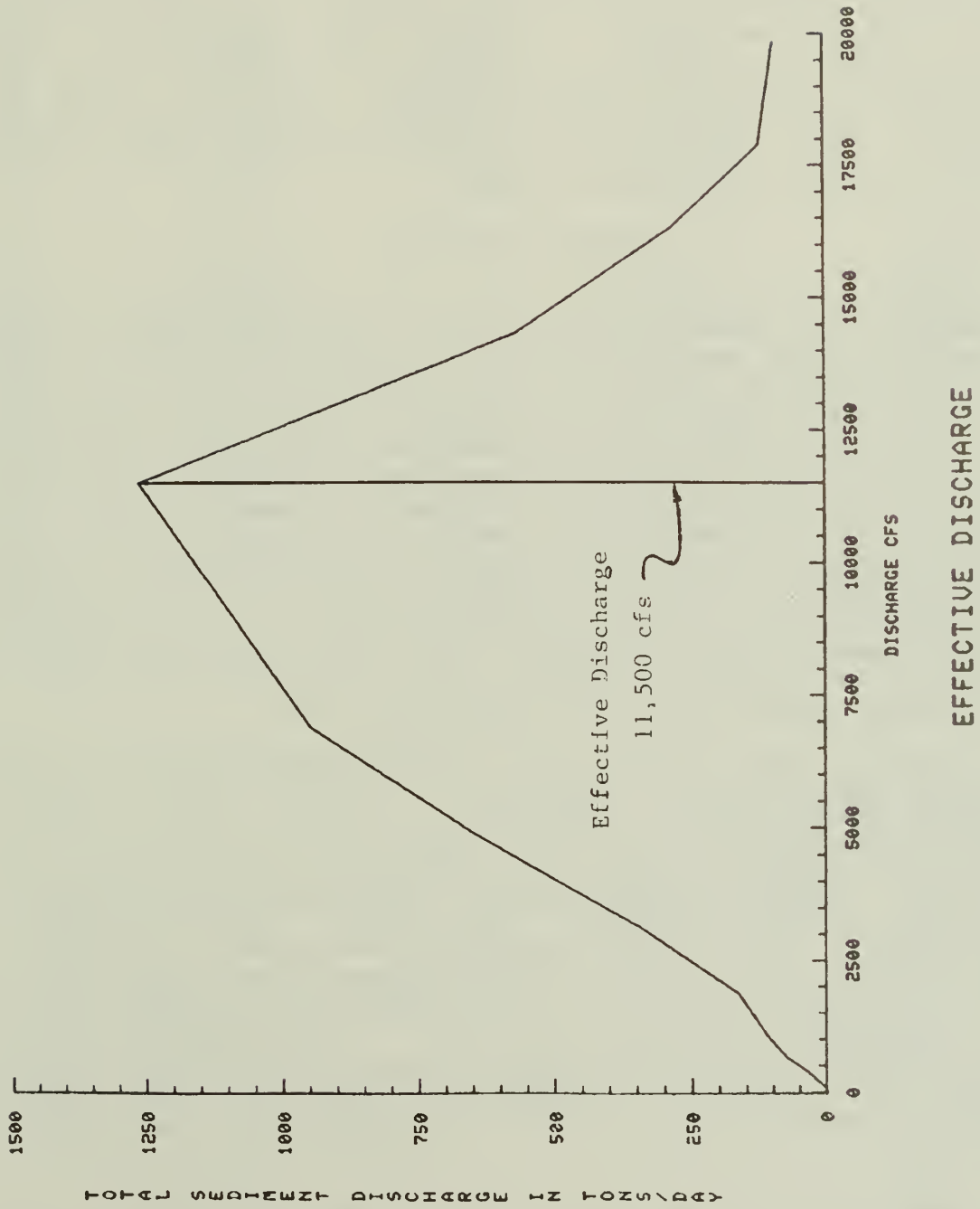


Figure 12

In the cobble reach, the Yampa River has incised a channel below the floodplain terrace. This incision has reduced the frequency of overbank flooding, and the bankfull discharge has a return period of 20 years. Bankfull discharge has also been determined to be the discharge which moves the median size bed material. This evidence supports the conclusion that the bankfull discharge is the channel forming flow. Channel morphology in the canyon is not adjusted with every seasonal variation in discharge. The dynamic nature of the cobble substrate reach is maintained by bankfull discharge which reforms the bar shape and orientation and reorders the substrate size distribution in local areas. Bedload transport of the large cobble substrate occurs with discharges in excess of bankfull discharge. The channel width will adjust to form the most efficient section for the cobble bedload transport. Rare floods, therefore, have the most significant effect on channel morphology in the Yampa Canyon.

Sediment Transport

There is no corresponding period of record for daily sediment discharge at the Maybell and Lilly gaging stations. Five years of daily sediment discharge measurements were collected by the USGS for water years 1960 through 1964 for the Little Snake and 1952 through 1958, 1976, and 1978 through 1982 for the Yampa, 13 years of record (see Table IV). For these short records the mean annual suspended sediment load was 1,341,300 tons for the Little Snake and 407,200 tons for the Yampa approximately 1,748,600 tons/year of suspended sediment delivered to the Monument. The mean annual flow during these years was 1,418,400 or 4.4% less than normal for the 1941-83 period. During this period, however, one extreme year of sediment discharge occurred for the Little Snake. If 4 days in 1962 (1,156,000 tons) are excluded from the analysis, the average annual suspended sediment load from the Little Snake is 1,110,100 tons per year and the mean annual suspended sediment load for the combined rivers is only 1,517,300 tons per year.

Compared to 1982, the 1983 field season at Mathers Hole incorporated improved data collection techniques, a greatly expanded sampling program, and collection of samples on both the rising and recessional limb. The '82 and '83 data are combined where appropriate in the analysis of sediment transport, but the 1983 data is generally used in obtaining sediment discharge versus water discharge regression relationships. These sediment regressions are presented in Table VI. The coefficient of determination (r^2) is higher for the recessional limb than the rising limb and the correlation between the sediment load and water discharge is excellent (see Figures 13 through 18). The Mathers Hole and Deerlodge suspended sediment rating curves are nearly identical (Figure 14). Excellent correlation was found with USGS measured suspended load at Deerlodge Park and is shown in Table V and Figures 13 and 14.

With these regressions and a flow-duration curve, and a load-duration analysis is performed on Mathers Hole data (Table V). The total suspended load using all the data from 1982 and 1983 is 1.91 million tons per year and alone, the 1983 suspended load is 2.13 millions tons per year. Applying the load-duration analysis to the

Table IV. Historical Sediment Data

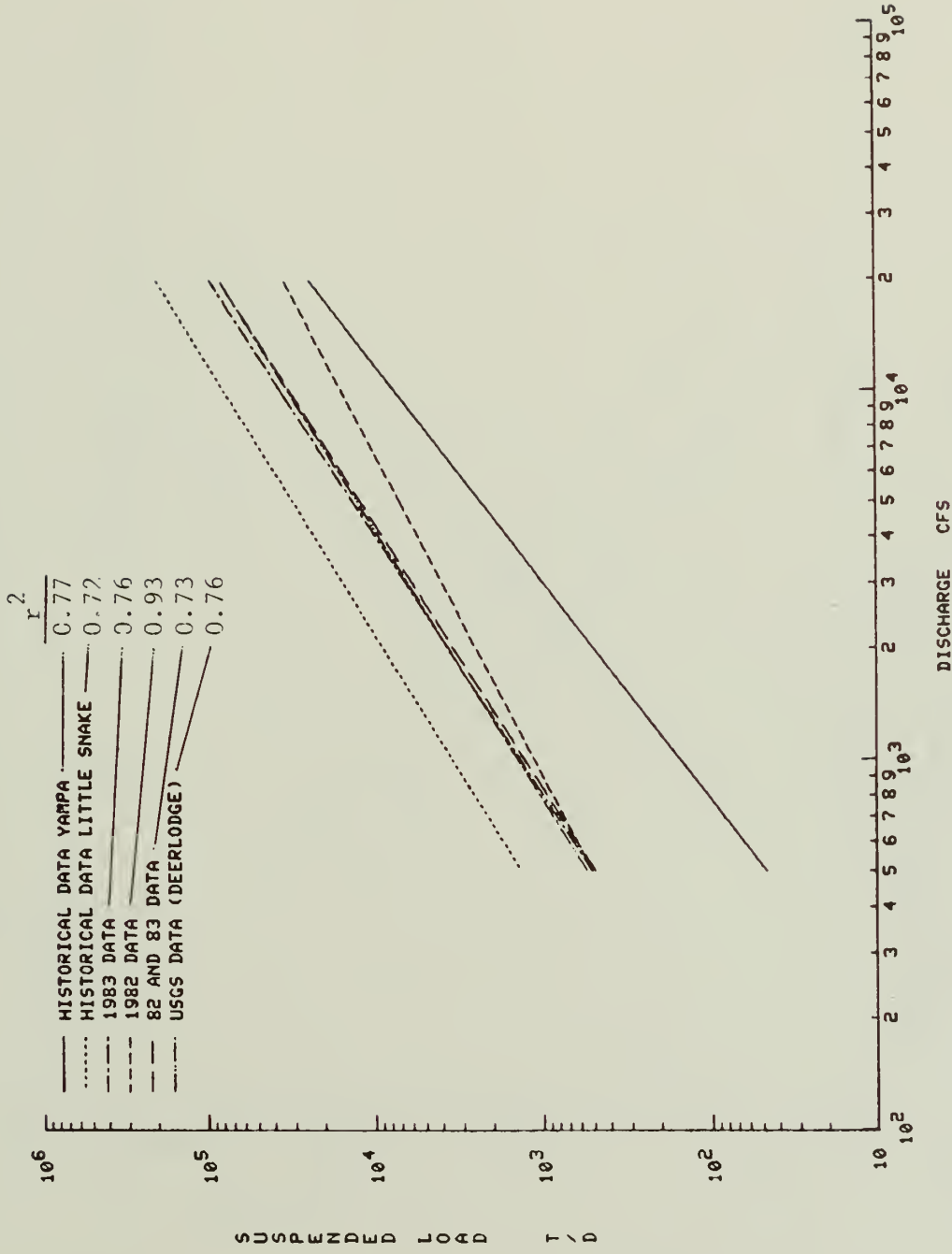
Water Year	Yampa, Maybell		Little Snake, Lilly	
	Discharge (acre-feet)	Sediment Load (tons/year)	Annual Discharge (acre-feet)	Sediment Load (tons/year)
1952	1,447,177	547,740	727,828	
1953	829,208	247,886	268,721	
1954	522,182	125,025	178,256	
1955	772,587	401,893	233,164	
1956	1,033,298	397,647	410,900	
1957	1,781,336	607,486	507,000	
1958	882,840	511,717	425,000	
1960	1,010,000		300,301	931,650
1961	629,300		162,779	438,142
1962	1,492,000		569,128	3,156,957
1963	630,200		203,601	958,285
1964	865,200		318,014	1,221,563
1976	826,300	246,508	382,400	
1978	731,628	500,450	507,000	
1979	660,582	232,540	417,500	
1980	645,121	651,042	557,400	
1981	279,388	187,247	248,300	
1982	692,174	618,903	570,100	
Average		407,237		1,341,319

Table V. Load Duration Analysis

	Annual Load (million tons/year)
1. Historical combined gaging stations, Maybell and Lilly	1.21
2. Same as #1 using seasonal analysis	1.20
3. USGS, measurements at Deerlodge	
a. Suspended Load	1.94
b. Sand Load	0.79
c. Total Load (including bedload)	2.04
4. Mathers Hole Data (1983)	
a. Fine Load (<0.0625 mm)	1.22
b. Sand Load	0.97
c. Helley-Smith Load	0.0062
d. Unmeasured Sands	0.038
e. Suspended Load	2.13
f. Total Load	2.16

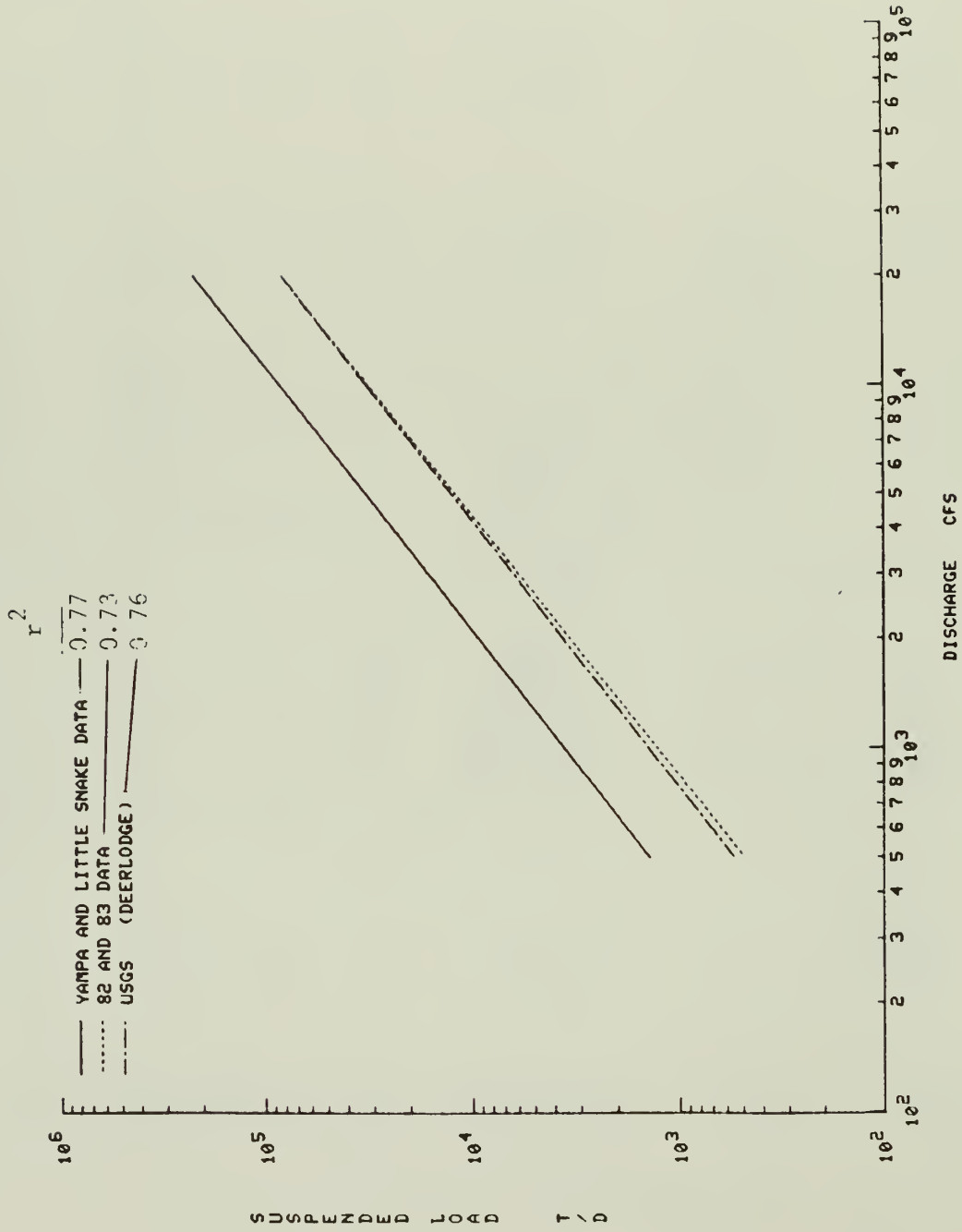
Table VI. Sediment Regression Relationships $Q_s = a Q^b$ (tons/day)

Description	No. of Points	Coefficient a	Exponent b	Coefficient of Determination r^2
Suspended Fines ($<.0625$ mm)				
Rising Limb, 1983	26	2.96×10^{-2}	1.497	0.84
Recessional Limb, 1983	14	4.57×10^{-3}	1.608	0.92
All Points, 1983	40	4.70×10^{-2}	1.408	0.80
Suspended Sand ($>.0625$ mm)				
Rising Limb, 1983	26	4.13×10^{-11}	3.742	0.94
Recessional Limb, 1983	14	4.69×10^{-10}	3.288	0.98
All Points, 1983	40	1.20×10^{-9}	3.283	0.91
Helley-Smith (unmeasured load)				
Rising Limb, 1983	29	2.91×10^{-5}	1.588	0.68
Recessional Limb, 1983	13	3.10×10^{-8}	2.436	0.80
All Points, 1983	42	1.07×10^{-6}	2.005	0.75
1982 Data	7	3.47×10^{-6}	2.041	0.85
All Points, 1982 & 1983	50	1.31×10^{-6}	2.012	0.70
Recessional Limb, 1982 & 1983	21	5.79×10^{-7}	2.167	0.71
Total Suspended Load				
Rising Limb, 1983	29	1.68×10^{-1}	1.352	0.75
Recessional Limb, 1983	14	6.54×10^{-4}	1.885	0.93
All Points, 1983	43	7.59×10^{-2}	1.417	0.76
1982 Data	7	9.57×10^{-5}	2.079	0.93
All Points, 1982 & 1983	52	8.55×10^{-2}	1.391	0.73
Recessional Limb, 1982 & 1983	22	1.48×10^{-3}	1.795	0.87
Unmeasured Sands				
Rising Limb, 1983	26	8.33×10^{-10}	3.074	0.93
Recessional Limb, 1983	14	2.54×10^{-8}	2.519	0.98
All Points, 1983	40	3.211×10^{-8}	2.585	0.88
Total Sediment Load				
Rising Limb, 1983	29	1.66×10^{-1}	1.354	0.75
Recessional Limb, 1983	14	6.51×10^{-4}	1.887	0.94
All Points, 1983	43	7.42×10^{-2}	1.421	0.76



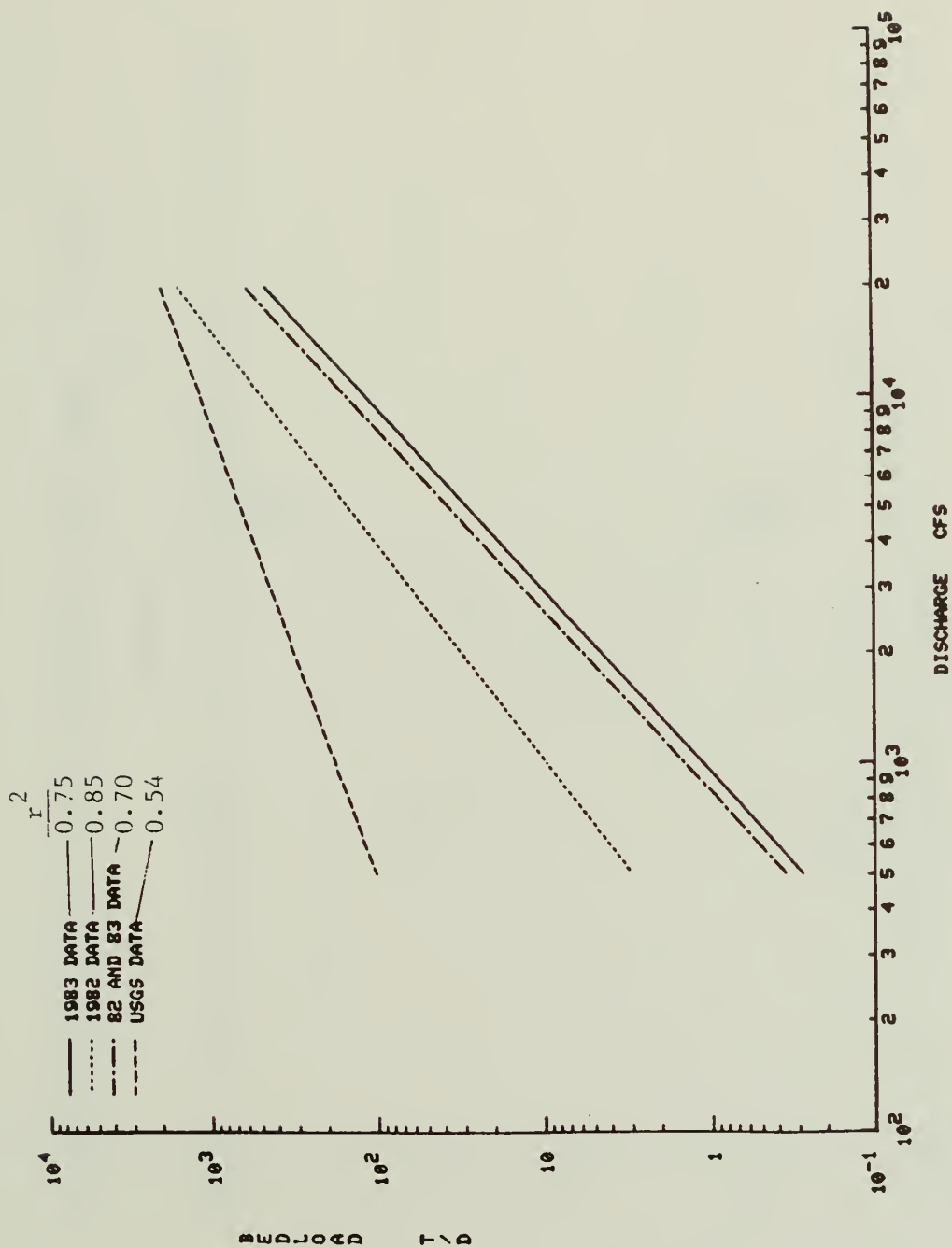
SUSPENDED LOAD REGRESSION PLOTS

Figure 13



SUSPENDED LOAD REGRESSION PLOTS

Figure 14



BEDLOAD REGRESSION PLOTS

Figure 15

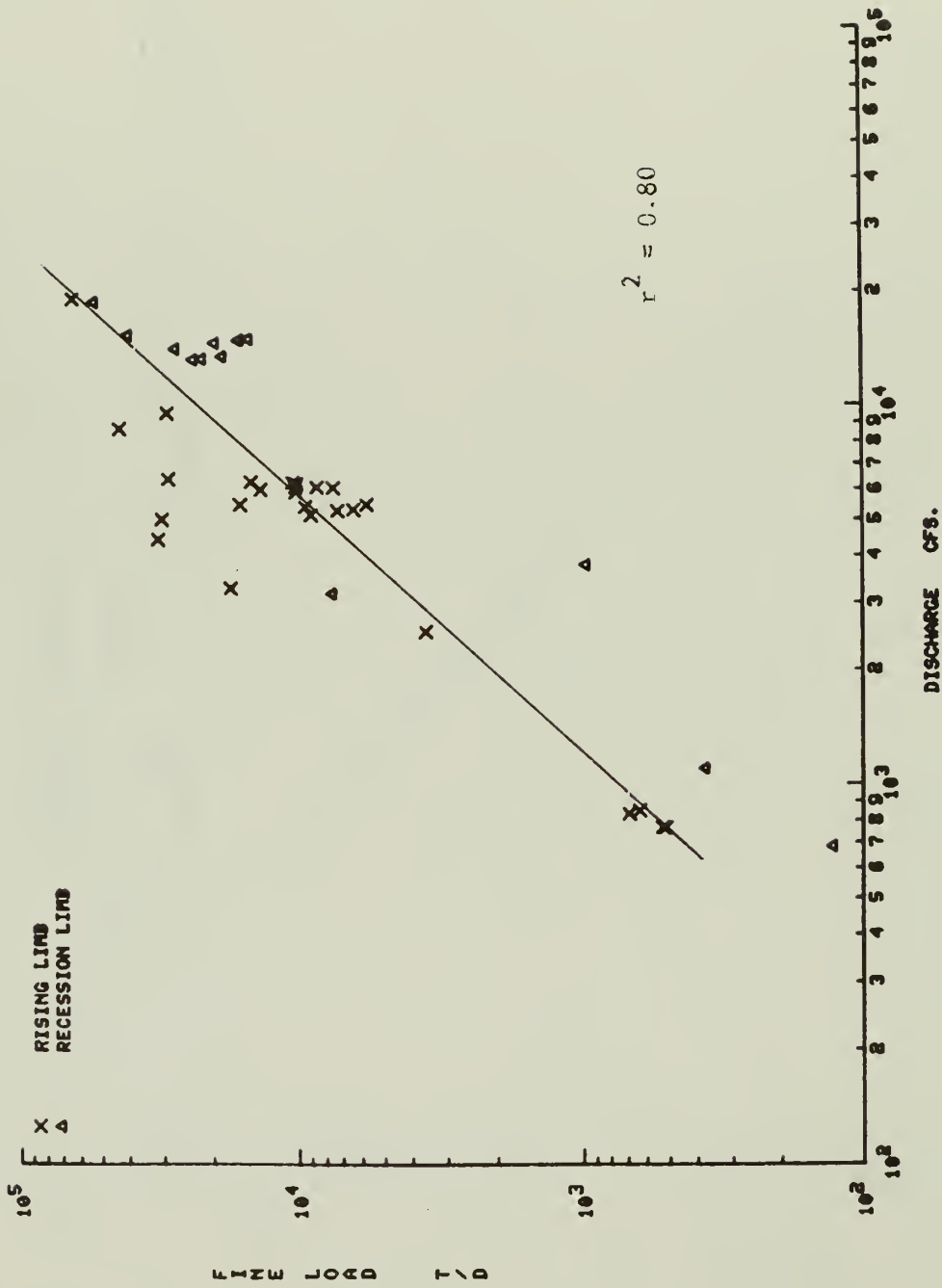
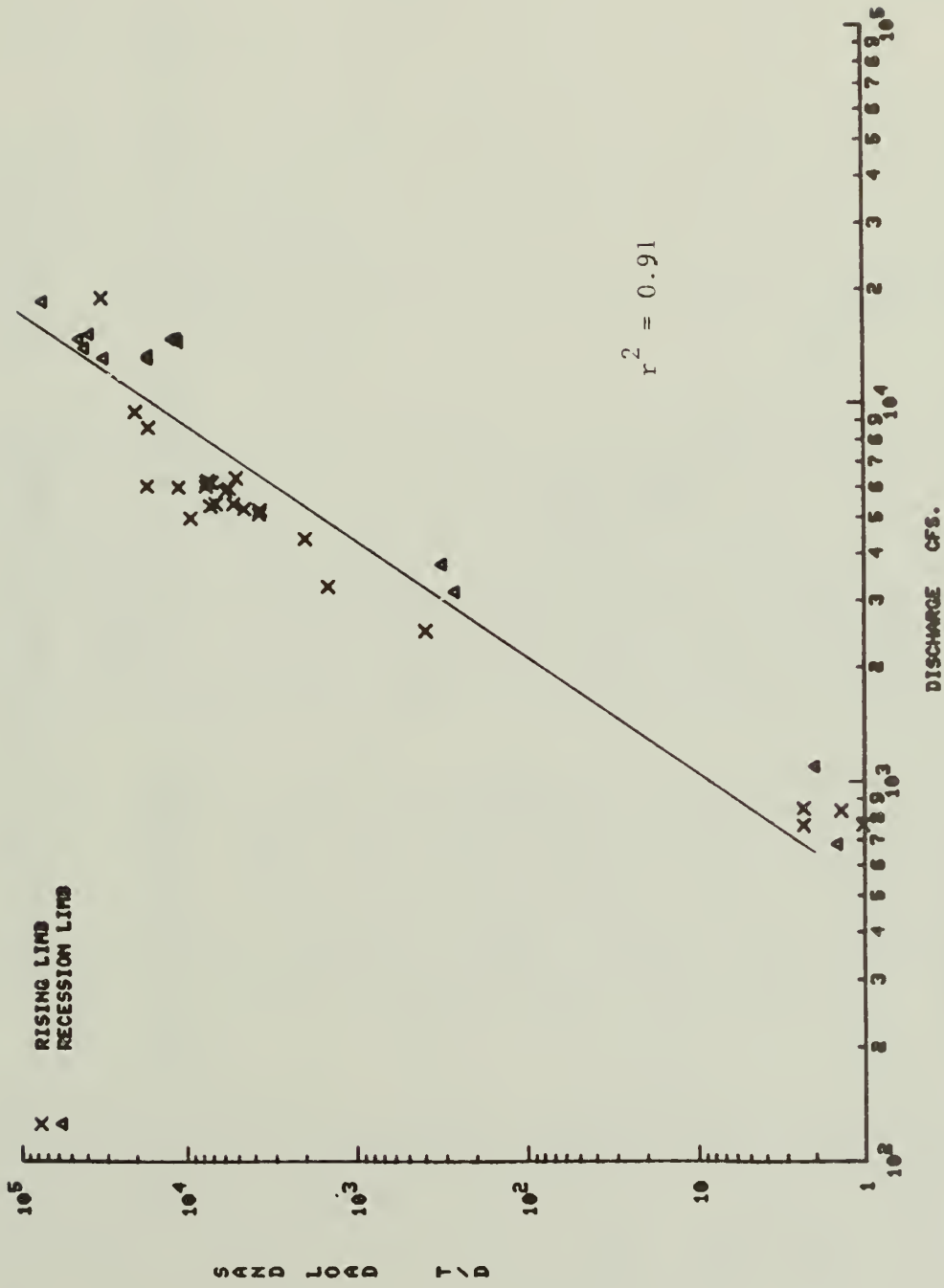
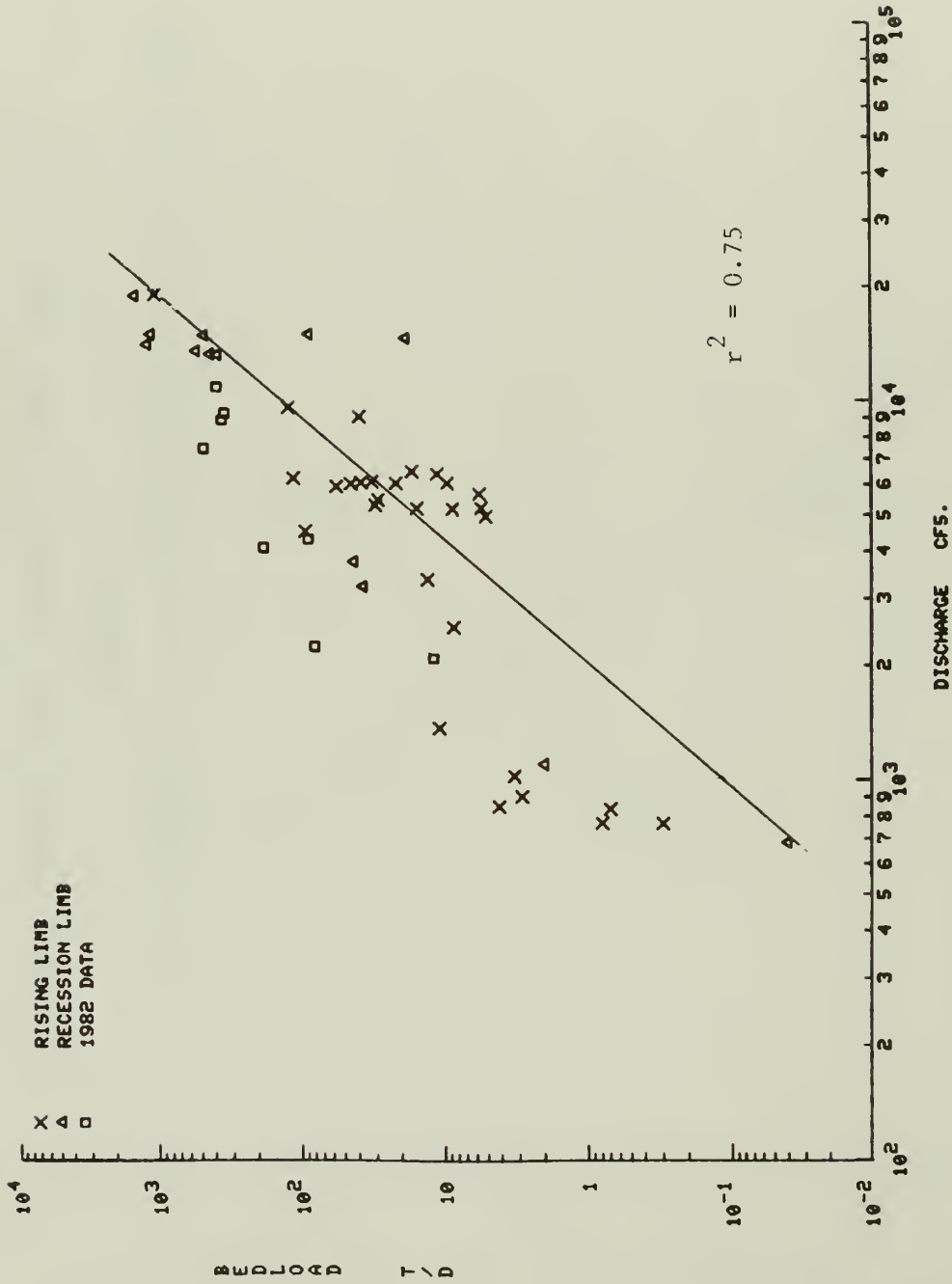


Figure 16



SEDIMENT RATING CURVE, MATHER'S HOLE 1983, SAND

Figure 17



BEDLOAD RATING CURVE, MATHER'S HOLE 1983

Figure 18

historical gaging station data, the average suspended load is calculated to be 1.20 million tons/year, significantly less than the average annual measured suspended load at the gaging stations and that calculated from the Mathers Hole data. Andrews (1980) reported the average sediment yield for the Yampa Basin at 2.0 million tons per year. The load-duration analysis when applied with log regression relationships of sediment and water discharge will underpredict the annual sediment load. The best estimate of an average annual sediment load is 1.5-1.6 million tons/year from the gaging station records. Last year's sediment load represents a substantial higher sediment yield for the basin.

The Helley-Smith sampler when combined with D-74 depth integrating suspended sampler is sampling, in theory, the entire flow zone of river. Only the sand sizes less than 0.25 mm which slip through Helley-Smith collection bag are missed in the sampling process. This sand fraction is referred to as the unmeasured sand load. The modified Einstein method for predicting total sediment load in the stream was applied to predict the unmeasured sand load. The results are presented in Tables V and VI. The unmeasured sand load was estimated to be 2% of the annual total load.

Nine sets of data were collected at Mathers Hole in 1982 and forty-three sample sets in 1983. A statistical comparison was undertaken to determine if any substantial differences in the measured sediment data could be discerned. The data was divided into two categories involving rising and recessional limbs of the hydrograph. The variables, total suspended concentration, suspended load, fine material load, and Helley-Smith load were tested. Assuming independent random samples of two normal populations with unknown means and variances, the t-test was used to accept or reject the hypothesis that there was no significant difference between the populations at the 5% significance level.

The statistic test was carried out using the Minitab statistical regression computing system. The results show that there was a significant difference between the rising and recessional suspended sand load, the rising and recessional Helley-Smith load, and the rising and recessional fine material concentration for 1983. Further, there were also significant differences between 1982 and 1983 recessional total suspended loads and between the 1982 and 1983 total suspended load and concentration for all the measured samples (see Table VII).

Substantially more sediment was transported through the Yampa Canyon in 1983 than in 1982. If discharge was the sole factor responsible for the increase in sediment loads, then essentially no differences would be detected in the sediment rating curves. The results show that the Helley-Smith load is the same from year to year, but variation occurs between the rising and falling limbs of the hydrograph. This may be explained by the coarse sand bedload travel time from the source area at Deerlodge to the Mathers Hole sampling site. The concentration and fine material load are relatively less for a given discharge on the falling limb than on the rising limb indicating

Table VII. Statistical Analysis of Sediment Discharge t-test
of Variables with Unknown Means and Variances

Variable	Description	Sample Size	Variance Hypothesis*
Q_s	1983 rising vs. recessional	26,14	Rejected
Q_f	"	26,14	Accepted
Q_{st}	"	29,14	Accepted
Q_{hs}	"	29,13	Rejected
C_s	"	26,14	Accepted
C_f	"	26,14	Rejected
C_{st}	"	29,14	Accepted
Q_{st}	1982 vs. 1983 recessional	14,9	Rejected
Q_{hs}	"	8,13	Accepted
C_{st}	"	9,14	Accepted
Q_{st}	1982 vs. 1983 all data	9,43	Rejected
Q_{hs}	"	8,42	Accepted
C_{st}	"	9,43	Rejected

where: Q_s = suspended sand load
 Q_f = suspended fine material load (<0.0625 mm)
 Q_{st} = total suspended load
 Q_{hs} = Helly-Smith load
 C_s = concentration of sands
 C_f = concentration of fine material
 C_{st} = total suspended concentration

*Hypothesis: No significant difference between the populations at the 5% significance level using the t-test.

a reduction of the supply of sizes less than 0.0625 mm. The difference in total suspended concentrations between 1982 and 1983 recessional limbs was not significant, but the water discharge accounted for a substantial difference in the total suspended load. Finally, the missing rising limb measurements in 1982 may account for the difference in total suspended concentration and load when compared with 1983 data. The foregoing analysis demonstrates the variability of the concentration and sediment load on a seasonal and annual basis. Since the sediment load in the river is supply limited, large differences should be expected from year to year.

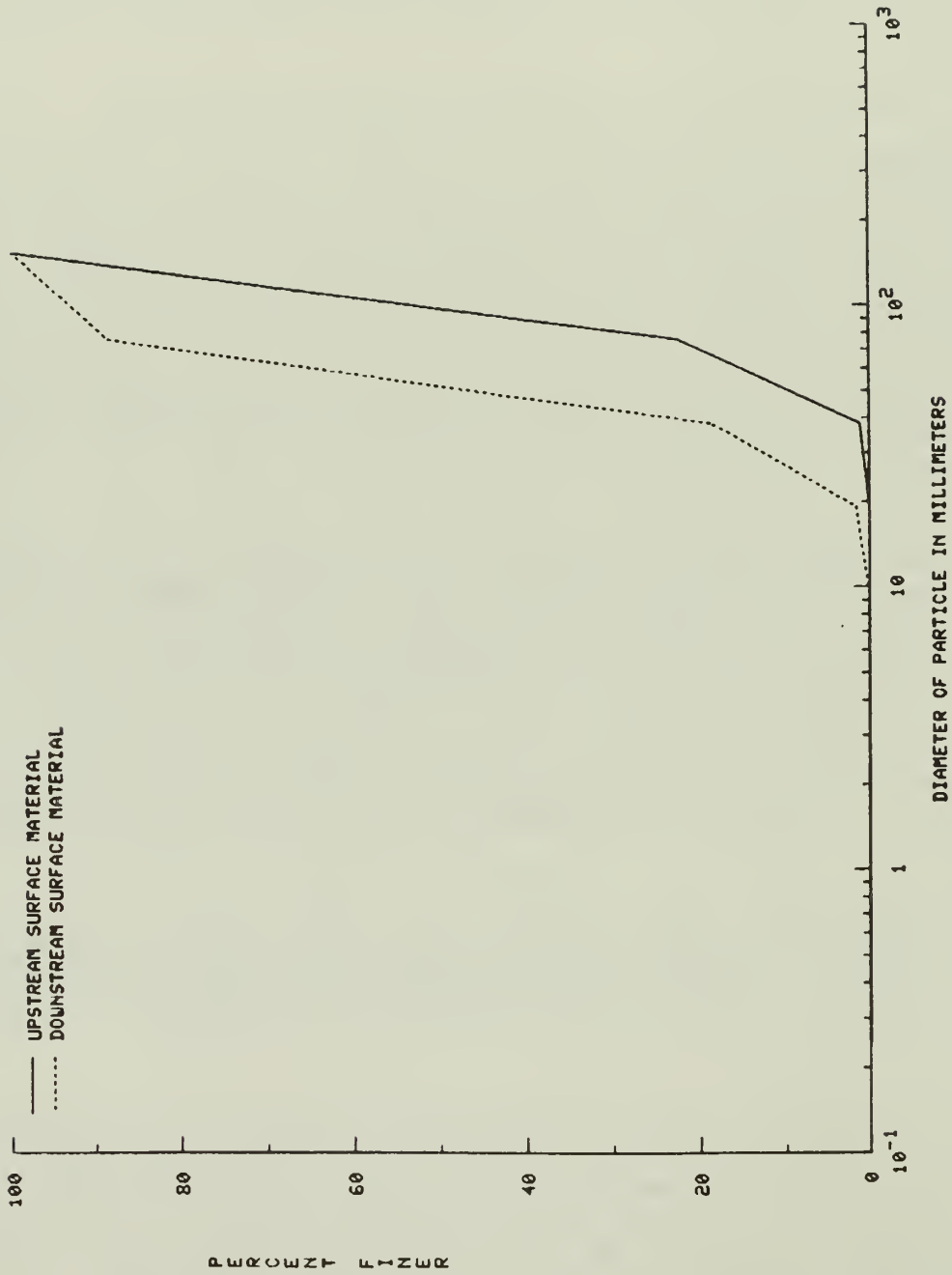
Transported Sediment and Substrate Size Distributions

Throughout the Yampa Canyon the bed material size is observed as a function of slope; steeper sloped reaches having boulder and cobble size substrate and the milder sloped reaches, gravels and sands. The upstream twenty miles, which are very steep with an average slope between .0024 and .0035, have angular boulder substrate. The study reach between river mile 16.5 and 20.5 has an average slope of approximately .0013 and a riffle-pool sequence with substrate of predominately cobbles. The bed material from river mile 16.5 to the confluence with the Green River, excluding Warm Springs rapid, is comprised mostly of small to medium cobbles, gravels and some sand and has a slope ranging from .00079 to .0011 (Figure 2).

The surface substrate of the cobble bars varies from the upstream tip to the downstream tip of the bar. The substrate D_{50} is 100 mm for the upstream portion of the RM 16.5 cobble bar and 50 mm for the downstream portion. The combined upstream and downstream substrate samples is 70 mm (Figures 19-21). This corresponds well with the D_{50} size of 75 mm for the cobble substrate at Mathers Hole. The porosity of the cobbles is about 0.42. This is a typical value for natural grain noncohesive material (standard Ottawa sand ranges from 0.33 to 0.44). All of the cobble substrate material is locally derived from side canyon tributaries or mass wasting processes on the talus slopes and bedrock walls.

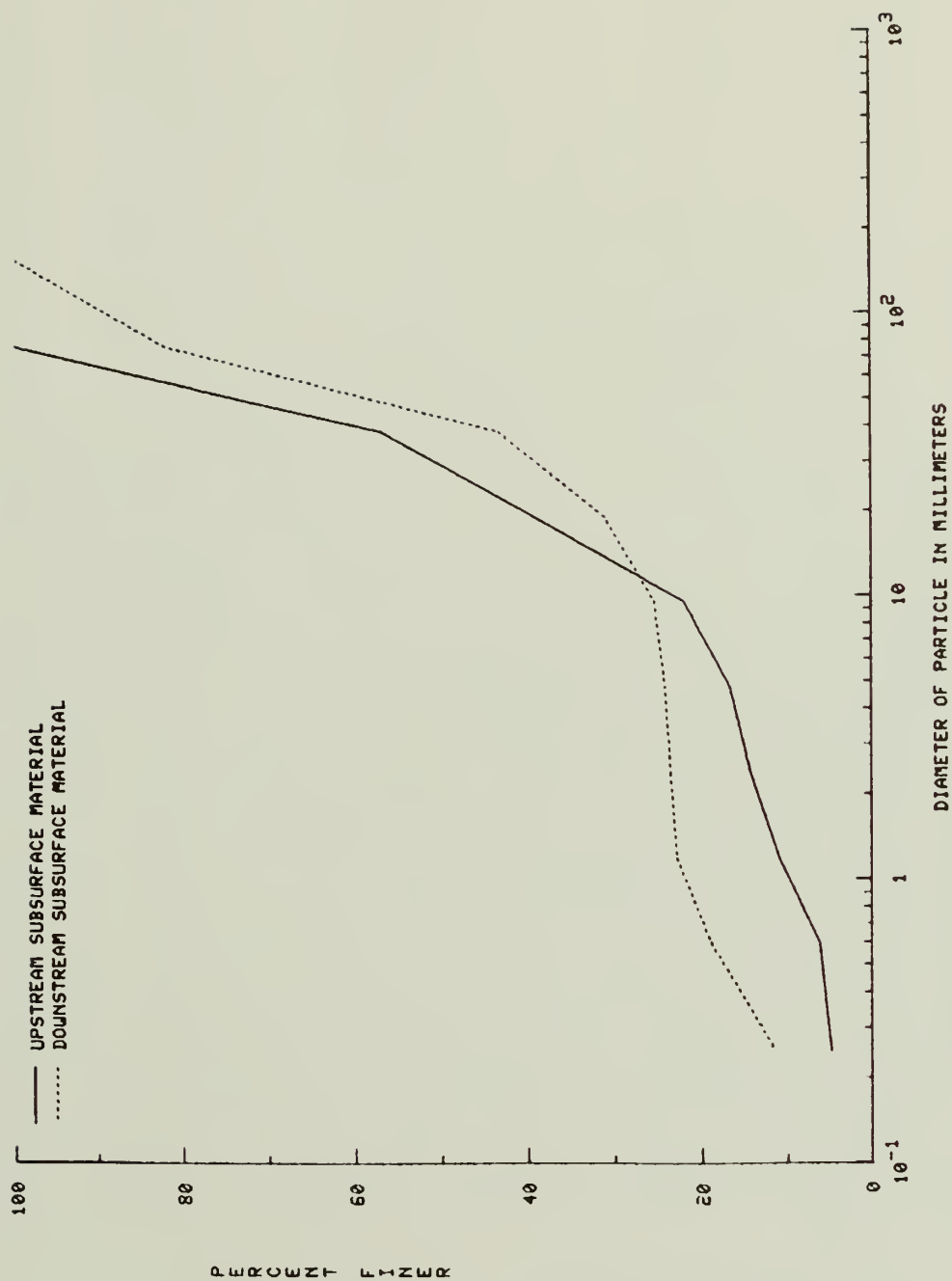
The wide range of grain sizes leads to two important features of bed heterogeneity, surface armoring and bimodal grain size distributions. Figure 21 reveals the armor nature of the surface bed material. Figure 20 shows a bimodal distribution in the subsurface substrate sizes. Transport modes depend on surface armoring and the availability of the finer sizes.

The Helley-Smith load is significantly coarser than the suspended sand load, but constitutes only 0.4% of the total load (Figure 22). Only the size fractions smaller than 1.0 mm were suspended high enough above the bed to be captured by the suspended sampler. The sediment particles greater than 1.0 mm (coarse sand) could be captured only by the Helley-Smith sampler and were not suspended higher than 3 inches above the bed. The median particle size captured in the sampler was 0.42. This is approximately one hundred-seventy times smaller the median bed material size indicating that all the transported sand is wash load. The Helley-Smith load median diameter is also seventy times smaller than the subsurface substrate.



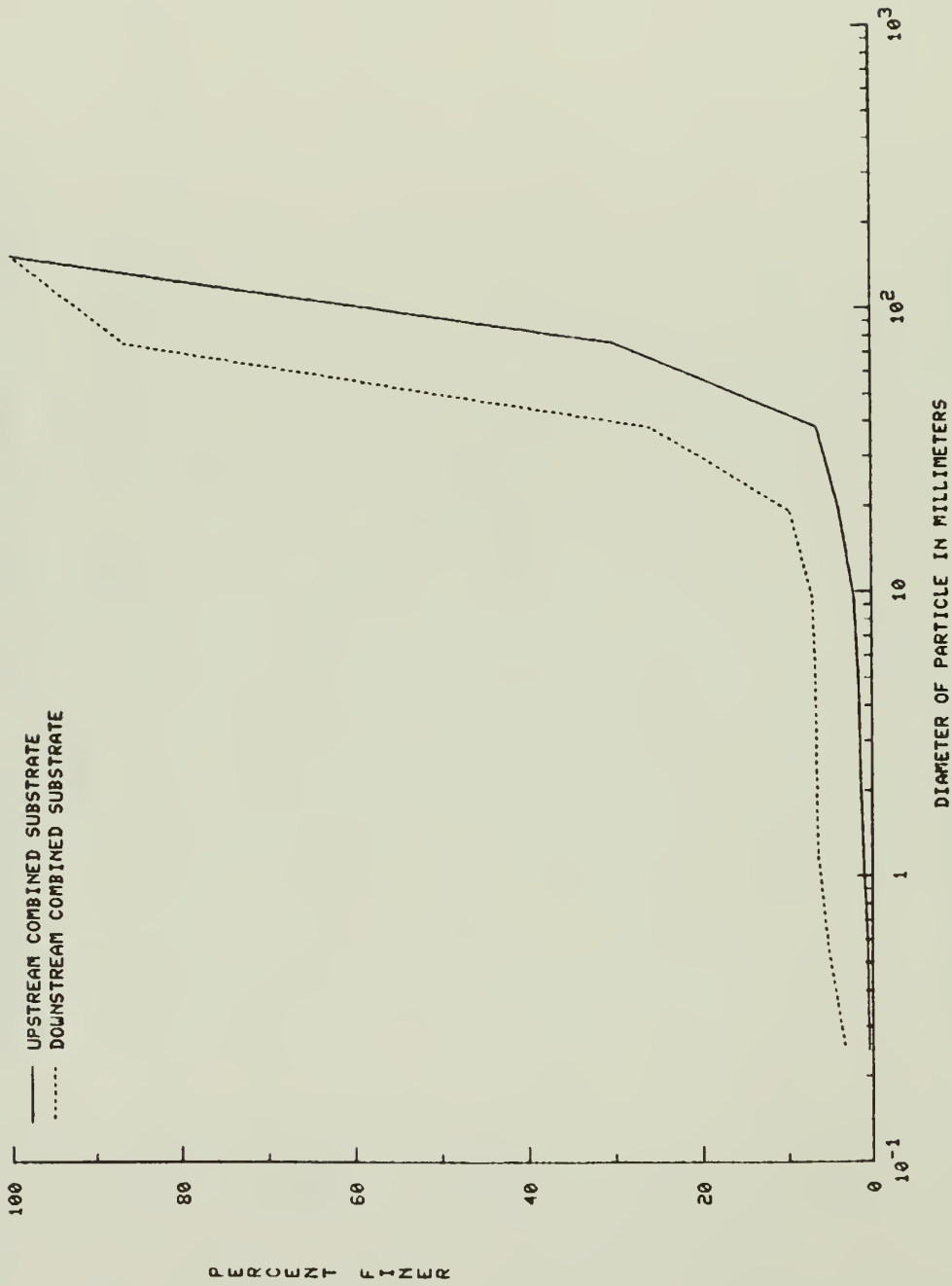
RIVER MILE 16.5 COBBLE BAR SURFACE SUBSTRATE

Figure 19



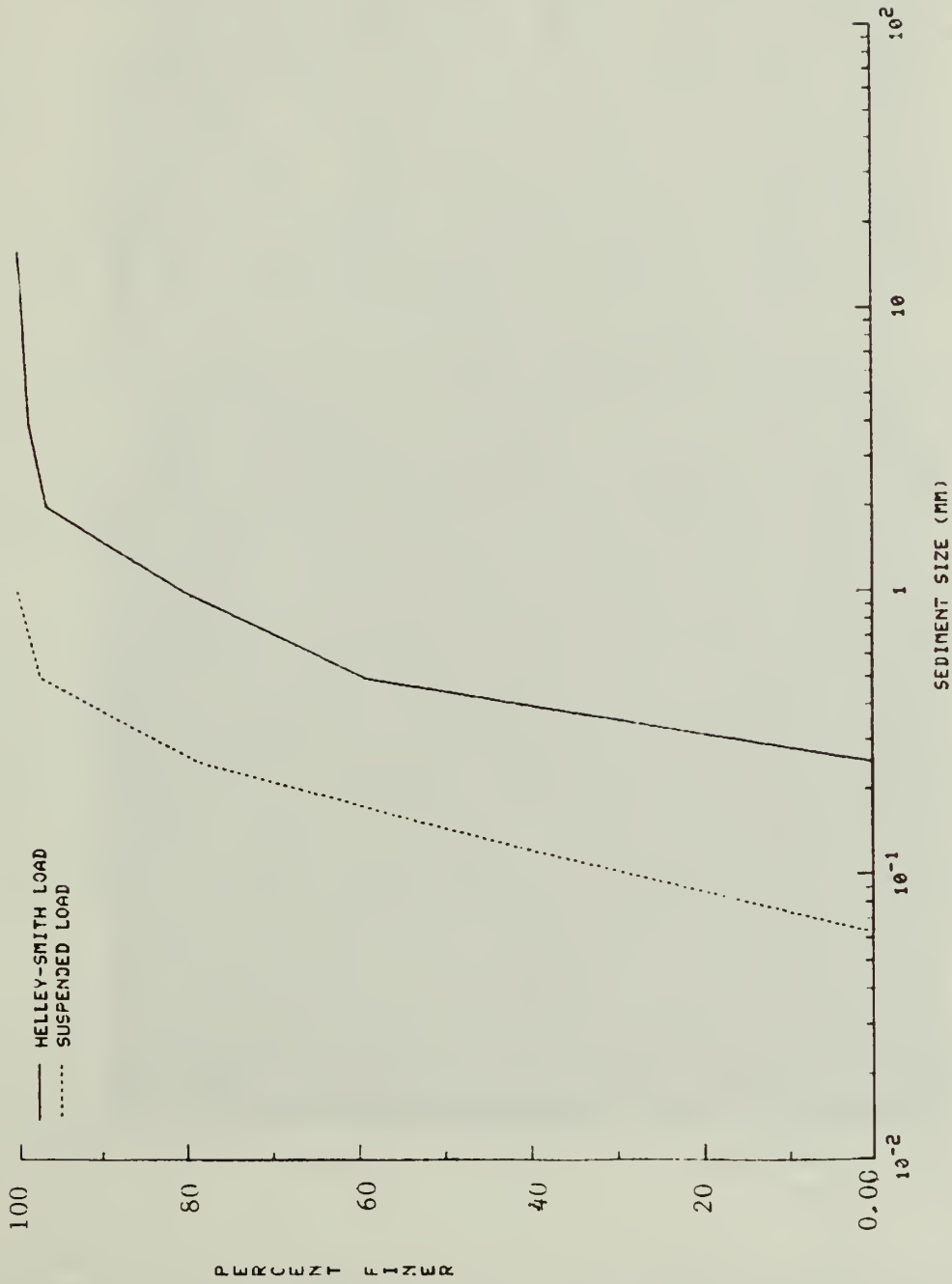
RIVER MILE 16.5 COBBLE BAR SUBSURFACE SUBSTRATE

Figure 20



RIVER MILE 16.5 COBBLE BAR COMBINED SURFACE AND SUBSURFACE SUBSTRATE

Figure 21



TRANSPORTED SEDIMENT SIZE DISTRIBUTION

Figure 22

The Helley-Smith sampler, from the peak flow (May 31) through June 24, collected gravels and cobbles moving on the bed. A total of 42 coarse gravels greater than 19 mm and five small cobbles were captured by the sampler. Most of the cobbles were disc-shaped.

Recent work by Andrews (1983) and Parker (1982) indicate that particles as large as the median diameter of the river bed substrate are entrained by discharges which equal or exceed the bankfull discharge. Entrainment of a given size particle has been shown to be a function of the bed material size distributions. Differential entrainment of the coarse bed fraction occurs in a relatively narrow range of shear stress (Andrews, 1983). From observations at Mathers Hole, the bedload consisted of relatively few large gravels and cobbles at the peak discharge, but included some of all particle sizes smaller than the median substrate size. General motion of the entire bed was not observed at Mathers Hole and changes in the cross section configuration could not be detected.

Using the entrainment criteria developed by Andrews (1983) for naturally sorted riverbed material, it has been determined that the critical dimensionless shear stress is approximately equal to 0.03 for the median substrate material ($D_{50} = 75$ mm). This is the same criteria used in last year's analysis referencing Parker's work (1982). The ratio of the threshold particle diameter to the median particle diameter of the subsurface bed material is the basis for determining the incipient motion criteria in Andrews' analysis.

Mobilization of the median bed material particle will ensue at approximately 21,500 cfs. All bed particles in the cobble reach, except the very largest, will be entrained at this discharge which corresponds to the bankfull discharge. Entrainment of the imbricated particles may require a larger critical shear stress. There is no evidence to support any prediction of large scale channel configuration change or erosion below bankfull discharge. This is required to create a mobile-bed phenomenon. Evidence shows that even in a 'mobile bed' of coarse particles, movement is limited to short leaps and hops, the bed load at any instant still be relatively small (Butler, 1977).

Physical Model Study

A physical model of the cobble substrate at river mile 16.5 was constructed in the eight foot flume at the CSU Engineering Research Center hydraulic laboratory to study the physical processes and measurement of sand transport over cobble substrate. A detailed description of the model investigation is presented in Appendix A. A discussion of the results follows.

The hydraulic and cobble substrate conditions of the channel at River Mile 16.5 were modeled on a one to one model to prototype basis (Photo 2). Three separate tests were performed. The purpose of the first test was to calibrate the sampling efficiency of the Helley-Smith bedload sampler on a cobble bed for a range of hydraulic conditions less than those required for incipient motion of the cobbles. The efficiency of the Helley-Smith was calibrated for hydraulic conditions over a sand



Photo 2. Simulated Cobble Bed, Physical Model Study

bed in the second test. The third test consisted of an investigation of sand scouring processes in cobble substrate. The data collected during these tests included water discharge, depth, mean velocity, velocity profiles, water surface slope, flume bed slope, Helley-Smith sediment load and total sediment load.

From the calibration tests of the Helley-Smith sampler, the following results are reported:

- 1) The Helley-Smith sampler will underpredict the sand bedload transport over a uniform cobble bed.
- 2) The sampler overpredicts for a sand bed with large transport rates.
- 3) Diversity of substrate improves the efficiency of the sampler.

The Helley-Smith sampler is sensitive to local hydraulic conditions on the bed. If the cobbles protrude above the sand bed level, sand will pass under the sampler nozzle resting on the top of cobbles (Photo 3). The sampler was more efficient in trapping the coarse size sand particles.

Numerous observations were made on the phenomena of sand transport over and sand scour from a cobble bed. This information is important to understanding the processes required to sustain a cobble bed relatively free of sand over a range of hydraulic conditions. Sand moves as bedload through the cobble bed material in a series of interrupted waves and strings. As expected the sand rolled and saltated in and around the cobbles, scouring upstream of a cobble and being deposited in the wake of the cobble.

The sand bed was nearly level throughout the flume at a depth of one half to one cobble diameter below the average cobble bed height. When a small sand wave progressed through the test section, the sand bed was approximately the same level as the average cobble height. When equilibrium conditions were established in the flume to simulate those conditions at the cobble bars in the field (including maximum bedload transport rates), the bed surface was approximately 75% cobbles and 25% sand (Photo 4). Where sand waves were found, the bed was 80 to 90% sand with only the large cobbles exposed. Even more prominent than the waves were strings of sand, parallel to the flow direction. These were observed in the field depicting high rates of bedload transport.

For the second test of the flume study, a six inch bed of sand was laid over the cobble substrate. During succeeding flume runs the sand bed was removed. Various bedforms were observed for different runs at different locations in the flume test section. In the lower regime, ripples and large dunes were noted; in the upper regime, the bed planned out with high transport rates (Photo 5). The sand creating the bedforms was significantly coarser than the original sand laid on the cobble bed. With several high velocity runs, the layer of sand and all the bedforms were removed and the cobble bed was once again exposed. Sand was removed progressively from upstream to downstream.



Photo 3. Helley-Smith Sampler Positioned for Bedload Collection, Physical Model Study



Photo 4. Equilibrium Conditions of Sand and Cobble Substrate, Physical Model Study



Photo 5. Sand Dune Formation over the Cobble Substrate, Physical Model Study

Sand is scoured out from between the cobbles as a result of turbulent bursts in the interstices. Vortex events were irregular and observed to be strongest where several cobbles, stacked on top of each other, protruded above the average height of the cobble bed. A scour pit developed beneath these stacks of cobbles, but was occasionally filled in when a dune bedform passed (Photo 6). The sand could be scoured to maximum depth slightly greater than one median cobble diameter below the surface. Velocities in the cobble interstices were too small to entrain the larger sand sizes long enough to secure passage between the cobbles and back into the main flow zone.

Figure 23 shows the rate of sand removal from the cobbles. A state of equilibrium was reached when the sand level was approximately one cobble diameter below the cobble surface. This level fluctuated with a passage of a sand wave by the point of observation. The three stations all displayed a similar response, reaching an equilibrium level approximately 160 minutes after the test was initiated. It is postulated that shear stresses large enough for incipient motion of the median cobble size particle are necessary to scour the sand level to greater depths. In the field, the sand level was approximately one-half to one median cobble diameter below the surface of the cobbles.

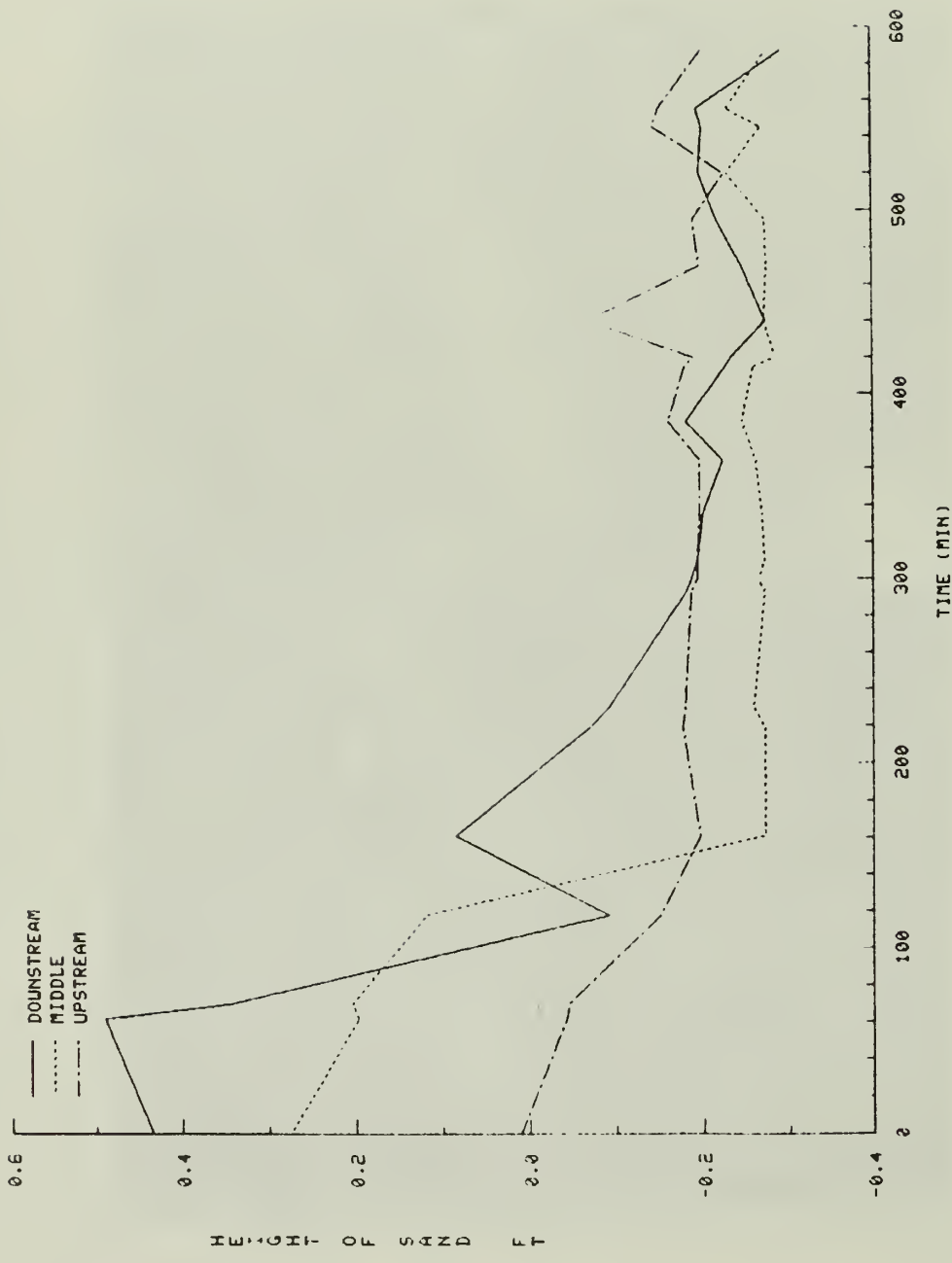
Dynamic Processes of Sand Transport over Cobble Substrate

The following discussion applies the results and observations from the physical model study to the field conditions. The effects of deposition of excessive amounts sands and fine material on the cobble substrate can be severe, limiting the aquatic insect population, reducing the capacity for spawning, and reducing the channel carrying capacity. The processes which insure a sand free cobble substrate are closely linked to a seasonal hydrograph shape and duration. The cobble bars have evolved upstream of wide bends to produce relatively short riffles of steep slope and high velocities that prohibit sand deposition. The pools upstream of the riffles have a sand substrate whose bed elevation fluctuates to seek equilibrium levels. The pool bed will scour at peak flows and will aggrade at low flow. There is evidence to suggest that the sand will migrate from a riffle to a pool during the base flow period (Rosgen, 1982).

On the rising limb of the hydrograph, sands are deposited in the interstices. These sands are interchanged between the bed and the suspended zone for discharges less than bankfull. Depending on the supply-capacity relationship, either deposition or scour could be occurring. Coarser sand sizes are transported as bedload in tortuous paths around the cobbles. When the cobbles move, the sand, of course, is washed from the interstices and may completely be removed from around the cobbles. At that point, sand will be released only when one of the armor particles is moved. Rearrangement of the cobbles will result in more stability of the armor layer. On the falling limb, the armor layer becomes a trap for sands until finally, the sand reservoir is again filled. Without cobble movement, sand will be scoured only to a depth of one-half to one median cobble diameter below the cobble bed surface.



Photo 6. Sand Scoured from the Cobble Substrate, Physical Model Study



SAND LEVEL IN RELATION TO TOP OF COBBLES

PHYSICAL MODEL STUDY

Figure 23

It was observed that at peak flows, portions of the cobble substrate were covered with sand to depths of one foot or more. These channel areas, outside the thalweg, are subjected to deposition as the sediment supply approaches transport capacity. Discharges of one-half the incipient motion of the armor layer will be capable of extracting sands and fines from the cobble substrate (Milhous, 1982). This corresponds to roughly the effective discharge for the Yampa River.

Mathematical Model Study

A quasi-steady water and sediment routing mathematical model was developed to simulate sediment transport in the cobble reach of the Yampa River. The field investigation of hydraulics and sediment transport was designed for the purpose of mathematically modeling a portion of the river to predict the river's response to various scenarios of simulated water and sediment discharge. Steepness precludes the necessity of modeling sediment transport in the first twenty miles of the canyon. A portion of the riffle-pool, cobble bar reach from river mile 16.5 to 20.5 was delineated for modeling.

The sediment supply for the model was the 1983 measured sediment data at Mathers Hole. Two cross sections downstream were surveyed as intermediate cross sections to the modeled area. Eight cross sections were monitored at the cobble bar area at river mile 16.5. Five of the eight were surveyed over the cobble riffle and three through the pool upstream (see Figure 3). In all, approximately one and one eighth miles of the four mile cobble reach were modeled. The model reach contained 3 riffles and 3 pools. The last riffle-pool sequence was modeled in its entirety. This sequence represents the complete range of hydraulic and sediment transport conditions and processes that are found in the four mile reach.

The model is constructed of a series of components, which have been universally applied in engineering predictions of sediment transport. The model in this study is a continuity model which keeps a budget of the incoming sediment supply, the transport capacity and sediment deposition or scour in each individual reach.

The quasi-steady water and sediment routing model is designed for determining channel aggradation and degradation in a river system. The river is divided into a series of computational reaches with similar hydraulic and geomorphic characteristics. Hydraulic conditions for each reach are calculated using the well-known and widely applied U.S. Army Corps of Engineers HEC-2 water surface profile computer program. The computed hydraulic conditions are then used to calculate sediment transport capacity for each subreach in the downstream direction. The sediment transport capacity is compared with the sediment supply from the previous subreach and the resulting aggradation or degradation is uniformly distributed both laterally and longitudinally in the reach.

The input discharge hydrograph is discretized into a series of time steps; each step represents a period of steady discharge. The sediment supply to the first cross section is similarly discretized for the same time steps. A new value for water and sediment discharge can be inputted

with each time step to simulate the gradually varied flow condition. A description of the sediment transport processes, model assumptions and model calibration are presented in Appendix B.

The results of the mathematical model study was a minimum streamflow hydrograph based on the predicted aggradation/degradation response to reduced water discharge. The minimum streamflow hydrograph was constructed to insure that a relatively sand free cobble bed is maintained in the modeled reach during the period from mid-July through mid-August. This criteria should be met on an annual basis for any given sediment supply scenario. The sediment supply to the upstream cross section represented by a sediment input hydrograph governs the resultant shape and timing of the simulated minimum streamflow hydrograph. Numerous sediment supply scenarios and water discharge hydrographs were tested utilizing both sediment-water discharge regression relationships and sediment hydrographs. In the final analysis the simulated hydrograph was based on the 1983 measured sediment load at Mathers Hole.

Combining the historical daily discharge with the simulated daily discharge, whichever is less, a composite hydrograph is developed (Figures 24-30). The results are presented in Table VIII. The minimum streamflow hydrograph has the following components:

Baseflow (August 16 - March 21)

Of the three periods of record analyzed, water years 1922-83, 1922-38 and 1941-83, the mean baseflow (367 cfs) of the 1941-83 period was chosen as reflecting the post-expansion conditions in the Monument.

Rising and Recessional Limbs (March 22 - July 12)

This portion of the hydrograph was defined by the criteria for maintaining the river mile 16.5 cobble bar essentially free of sand in July and early August.

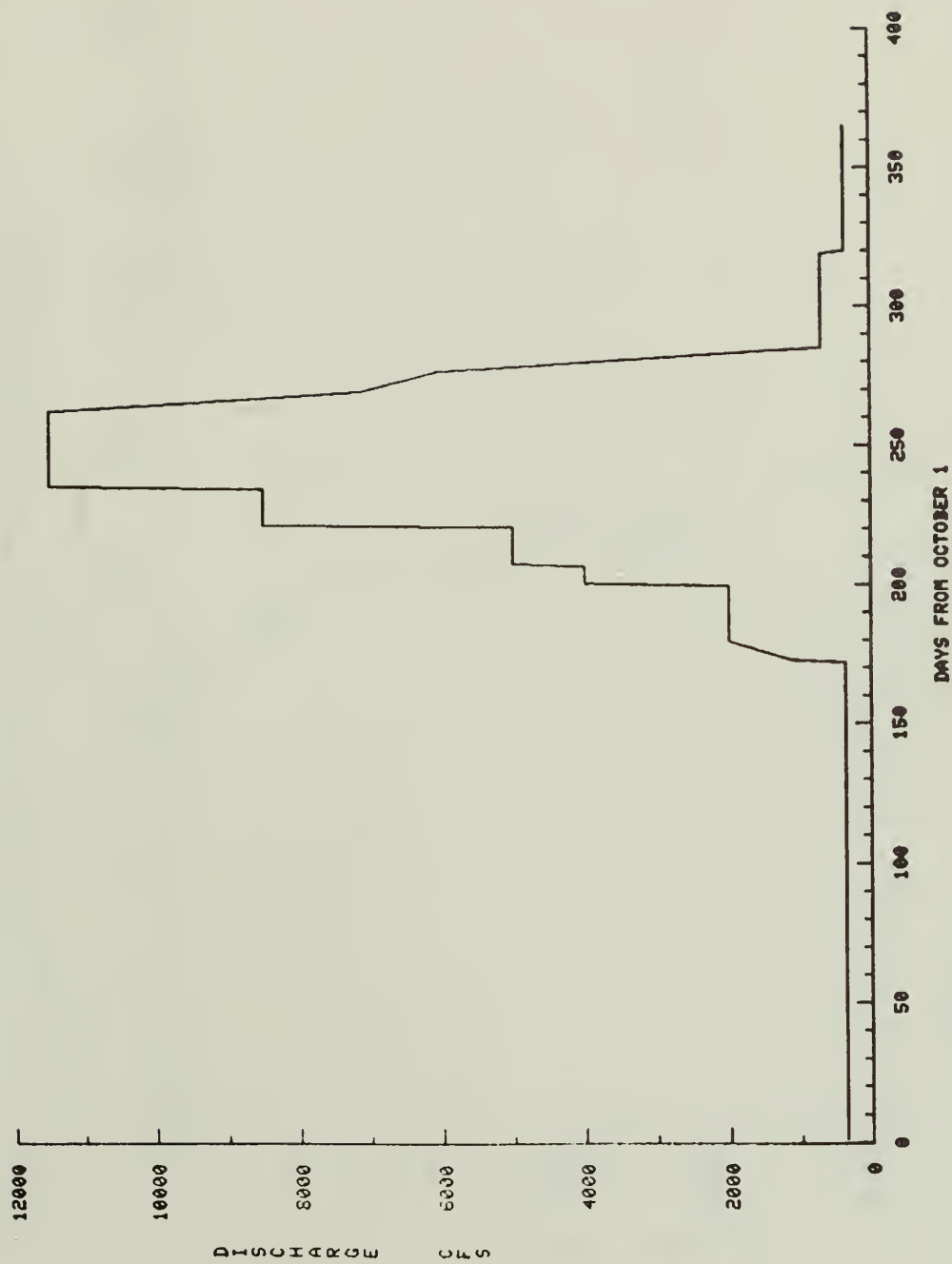
Colorado Squawfish Spawning Flows (July 12 - August 15)

The PHABSIM computer model predicted 700 cfs to be the optimal flow for spawning.

Peak Flow (May 24 - June 20)

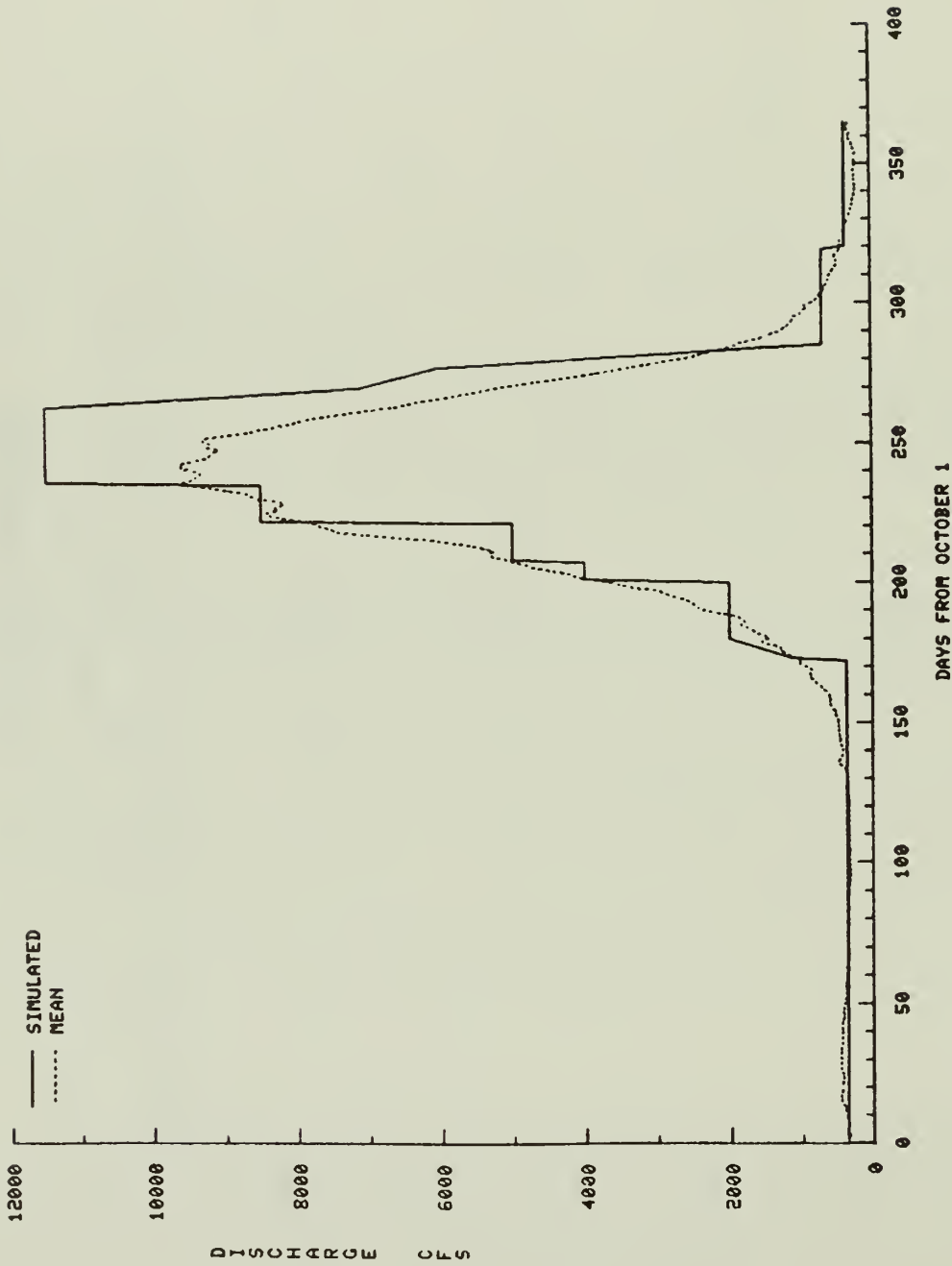
The peak flow of 11,500 cfs is the computed effective discharge at Mathers Hole based on sediment rating curves. A channel flushing flow of 48 hours of natural peak is included in the composite hydrograph. When the simulated discharge equals or exceeds the 11,500 cfs peak, then the actual peak discharge and next daily discharge less than or equal to 21,000 cfs is included in the simulated hydrograph. This constraint is reflected in Table VIII in computing the composite volumes but was not used in the computer model.

The various components of the hydrograph are connected by step increments. One week steps were utilized in the model. A single value of water and sediment discharge representing the average for the week



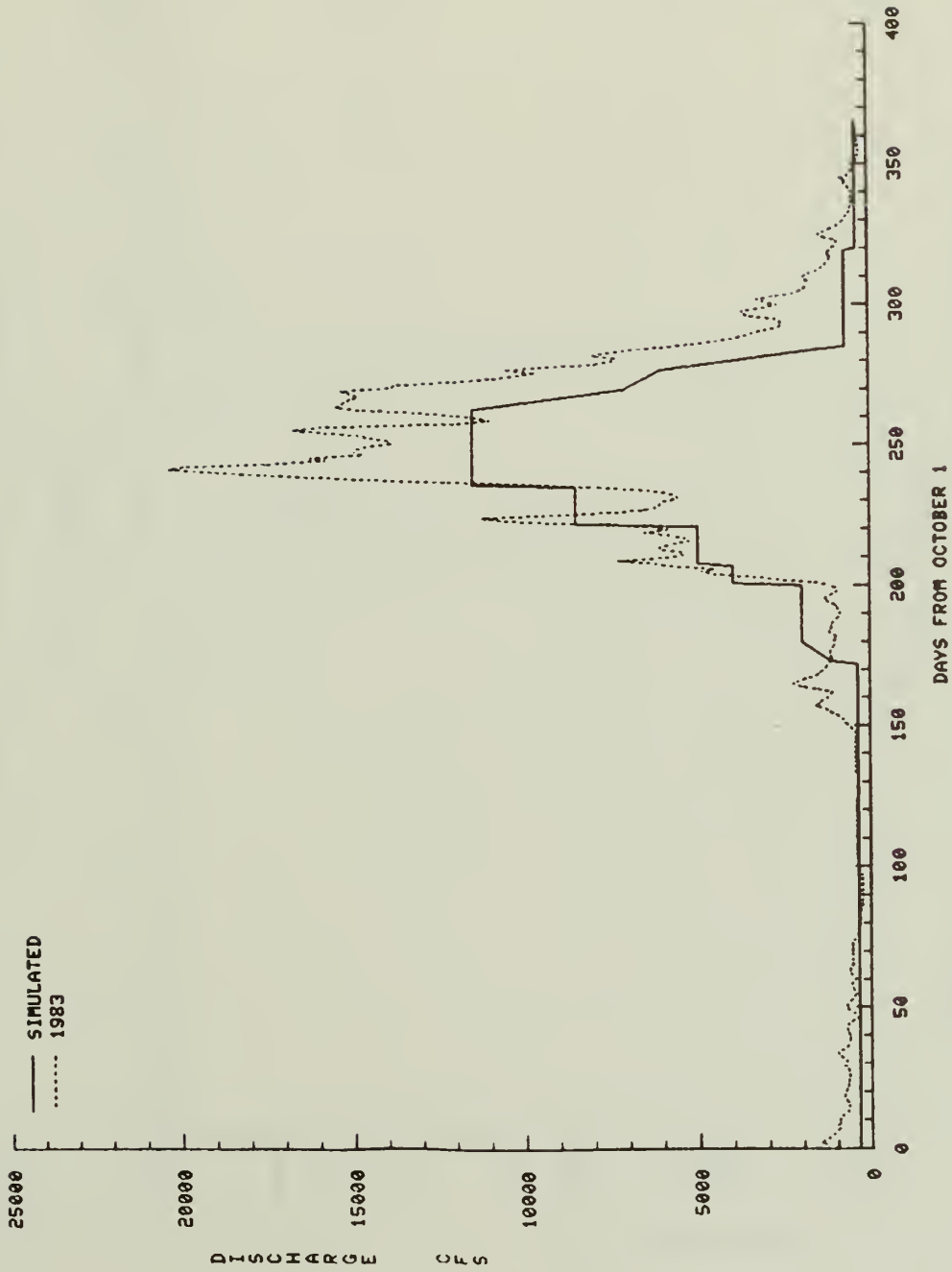
SIMULATED HYDROGRAPH

Figure 24



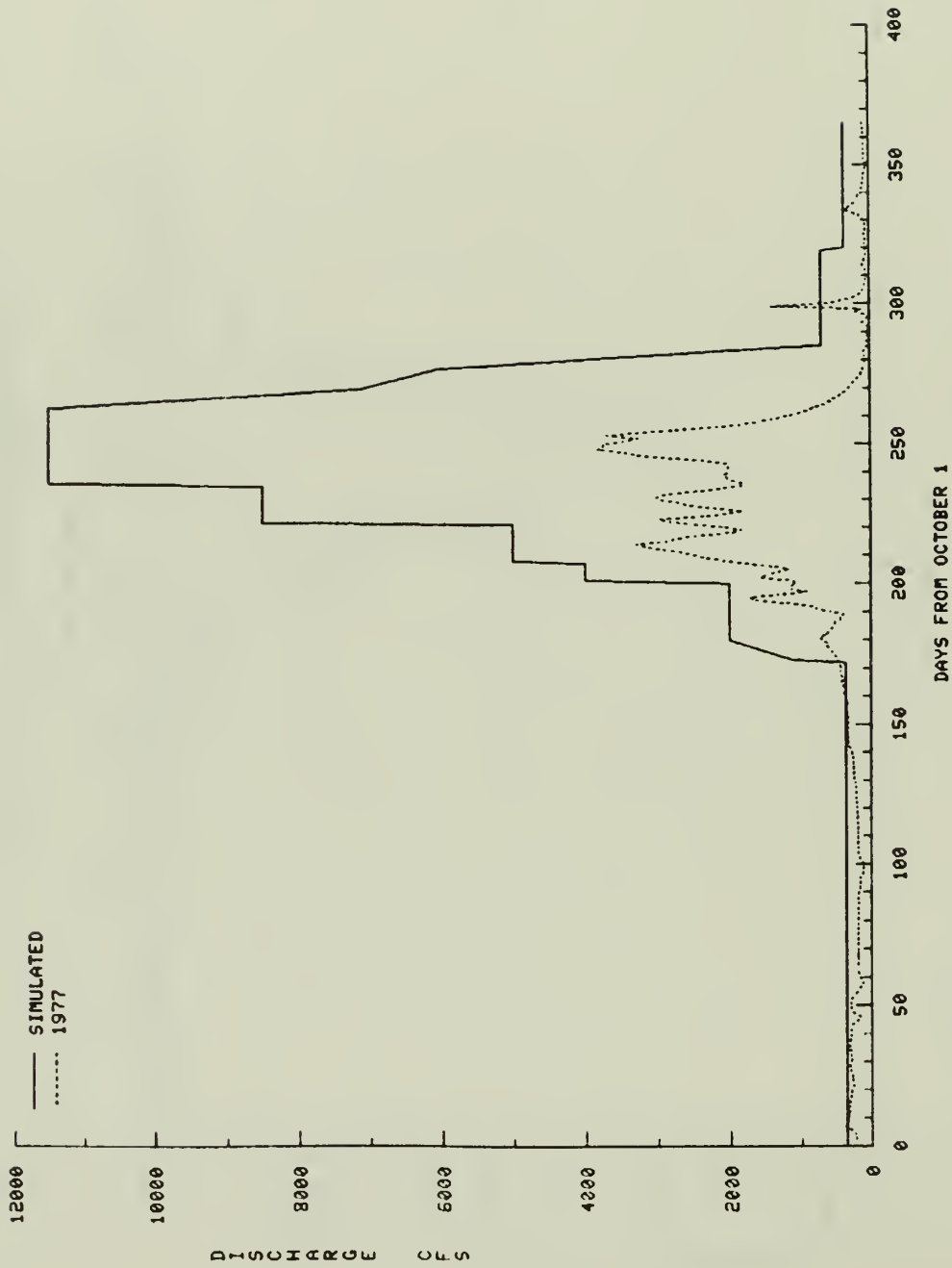
SIMULATED AND MEAN ANNUAL HYDROGRAPHS

Figure 25



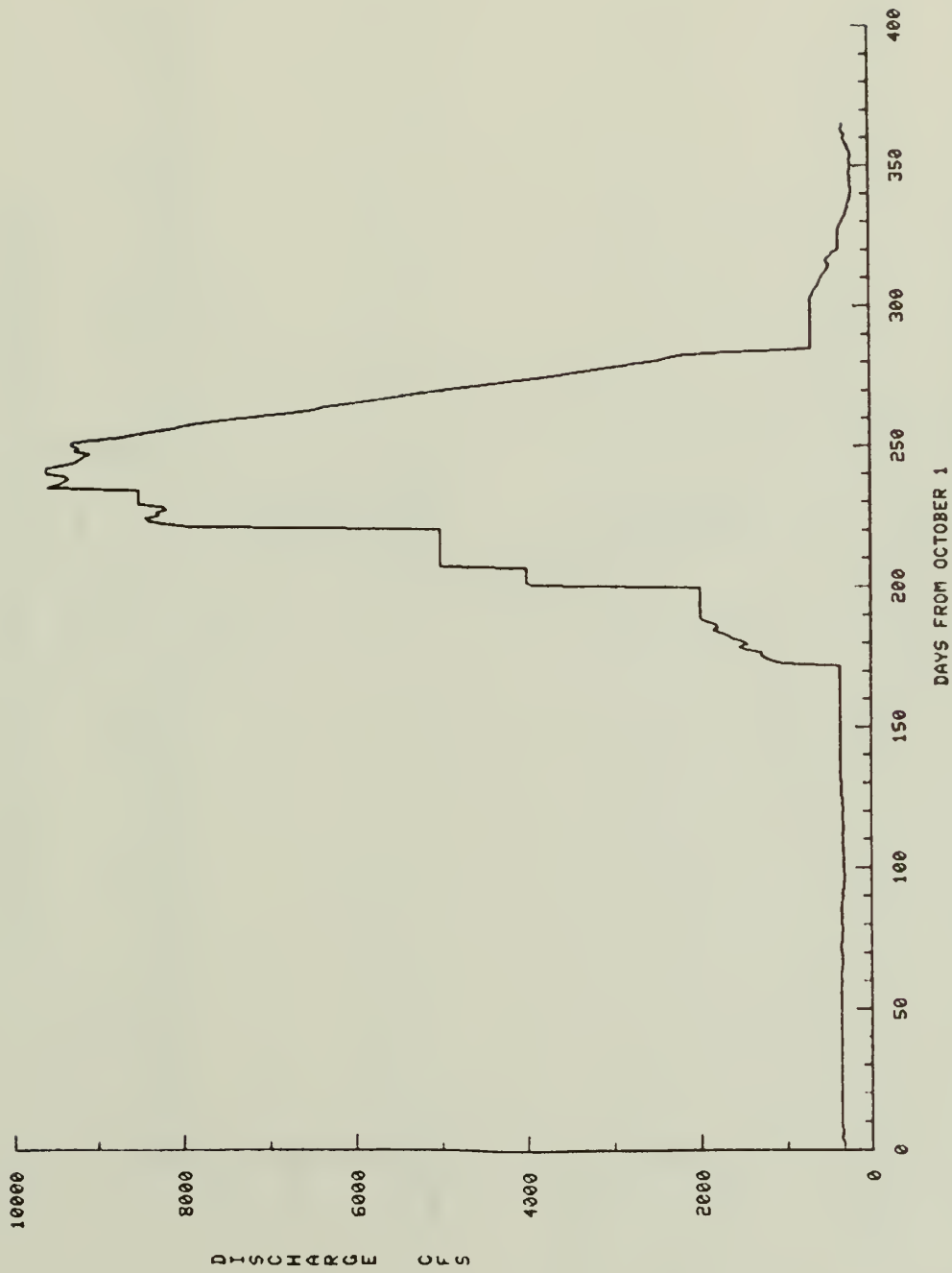
SIMULATED AND 1983 HYDROGRAPHS

Figure 26



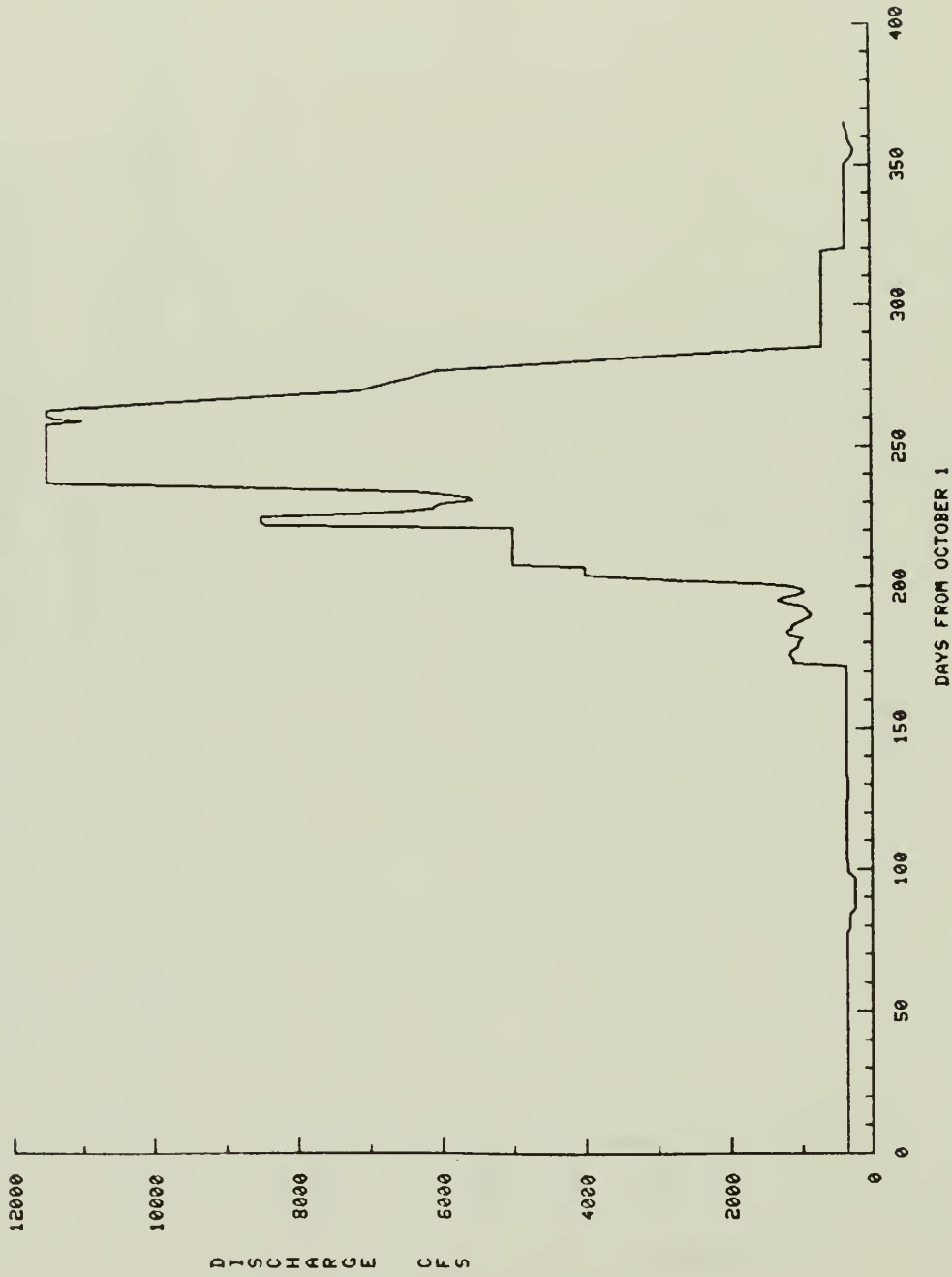
SIMULATED AND 1977 HYDROGRAPHS

Figure 27



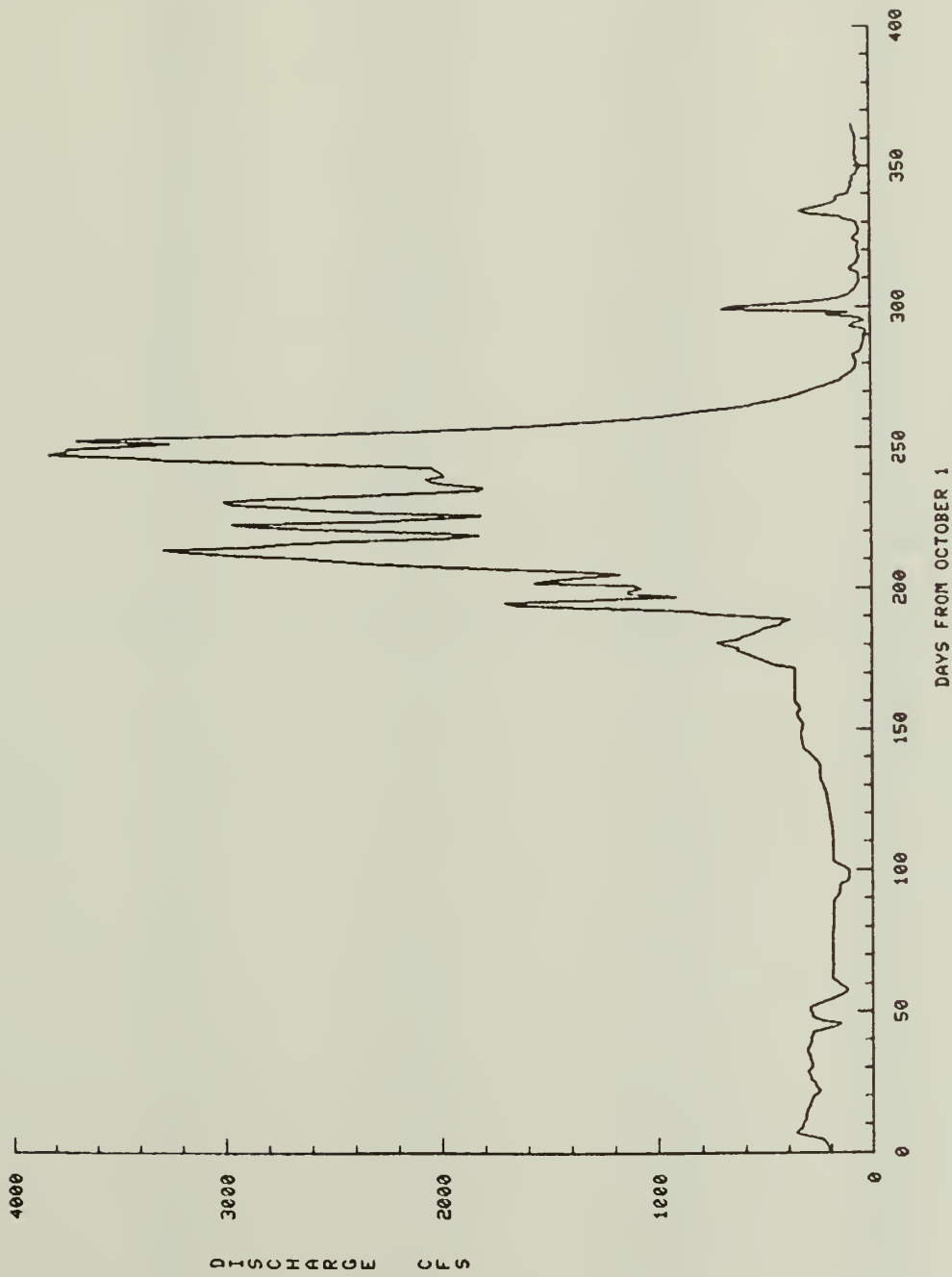
SIMULATED AND MEAN ANNUAL COMPOSITE HYDROGRAPH

Figure 28



SIMULATED AND 1983 COMPOSITE HYDROGRAPHS

Figure 29



SIMULATED AND 1977 COMPOSITE HYDROGRAPH

Figure 30

Table VIII. Historical and Composite Hydrograph Volumes

Water Year	Annual Volume (acre-feet)	Composite* Volume (acre-feet)	Surplus Volume (acre-feet)
1922	1584567.	1373542.	211025.
1923	1838252.	1492852.	345401.
1924	1347465.	1188158.	159307.
1925	1408446.	1144597.	263849.
1926	1691386.	1243645.	447741.
1927	1887604.	1455036.	432568.
1928	2106429.	1438478.	667952.
1929	2902553.	1666846.	1235707.
1930	1359346.	1025009.	334337.
1931	1265287.	1024807.	240480.
1932	2144967.	1536915.	608052.
1933	1599209.	1399347.	199861.
1934	454095.	442003.	12091.
1935	1120021.	1099329.	20692.
1936	1508971.	1149219.	359751.
1937	1426433.	1203835.	222598.
1938	1708732.	1362918.	345813.
1939	1233386.	998250.	235136.
1940	1106580.	989908.	116671.
1941	1384672.	1172445.	212227.
1942	1649526.	1324488.	325038.
1943	1244955.	1071605.	173350.
1944	1241415.	1190361.	51053.
1945	1722819.	1391472.	331348.
1946	1179419.	980583.	198836.
1947	1777476.	1372634.	404842.
1948	1466055.	1181326.	284729.
1949	1857943.	1540234.	317709.
1950	1393951.	1272148.	121803.
1951	1310703.	1256181.	54521.
1952	2175005.	1435249.	739756.
1953	1097929.	1077069.	20860.
1954	700438.	685484.	14954.
1955	1005751.	945643.	60108.
1956	1443543.	1173840.	269702.
1957	2289240.	1519630.	769610.
1958	1693288.	1292853.	400435.
1959	1029978.	999768.	30211.
1960	1310152.	1078477.	231675.
1961	792112.	770351.	21761.
1962	2060738.	1284737.	776001.
1963	833860.	805159.	28701.
1964	1184427.	1112846.	71581.
1965	1793325.	1473791.	319534.
1966	1008993.	794151.	214843.
1967	1253888.	1189893.	63996.
1968	1622582.	1445549.	177033.
1969	1508031.	1213968.	294062.

Table VIII. Continued.

Year	Annual Volume (acre-feet)	Composite* Volume (acre-feet)	Surplus Volume (acre-feet)
1970	1869818.	1497743.	372075.
1971	2112790.	1571295.	541495.
1972	1266828.	1107146.	159682.
1973	1751740.	1429656.	322085.
1974	1956125.	1453260.	502865.
1975	1639329.	1373772.	265557.
1976	1207034.	1116926.	90108.
1977	448427.	445801.	2626.
1978	1958202.	1562967.	395234.
1979	1727802.	1449511.	278291.
1980	1835731.	1449718.	386013.
1981	802459.	776259.	26200.
1982	1943124.	1564392.	378731.
1983	<u>2246512.</u>	<u>1554124.</u>	<u>692388.</u>
Average	1507933.	<u>1219987.</u>	287946.

Volume of the simulated hydrograph is: 1644185. acre feet

*Composite volume is the summation for the year of the daily discharge or the simulated daily discharge whichever is less.

was associated with each step. This methodology does not allow for rapid changes in discharge. Only general aggradation and degradation is analyzed by the model; local scour, storm inflow, and hydrograph fluctuations are neglected.

Cross section subreach 5 (Figure 3) was determined by the model to be sensitive to aggradation and degradation of transported sand. It is also the reach where substantial amounts of aggradation could influence distribution of water discharge around the cobble island. The next subreach upstream of cross section 5 is predominantly sand bed and the downstream reach, mostly cobbles.

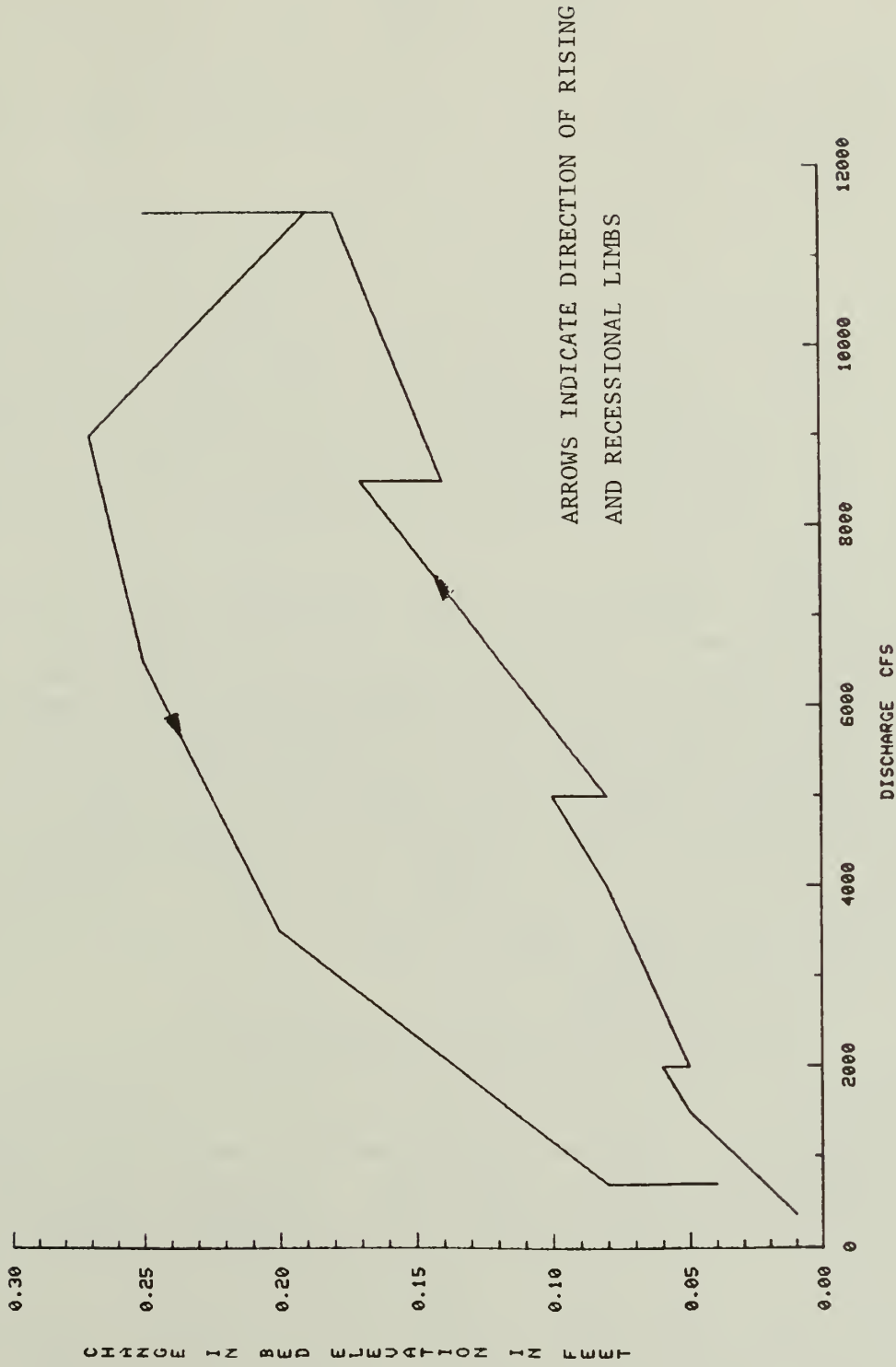
Water discharge input was varied to show how sensitive each subreach was to sand deposition. Incremental discharges were input until most of sand deposited is removed and does not exceed one-half of the median cobble diameter in thickness after July 11th. Figure 31 shows the bed elevation response to the simulated discharge hydrograph at subreach 5. Sand is deposited during the rising limb of the hydrograph and removed during the recessional limb.

Table VIII reveals the relationship between the simulated hydrograph and all the years of historical data. The first column is the combined Lilly and Maybell gaging stations annual volume. The volume of the simulated hydrograph without the 48 hours of natural peak is 1,644,185 acre-feet listed at the bottom of the table. The composite volume is the summation of the minimum of the actual daily discharge and the simulated hydrograph daily discharge. This composite (column 2) includes the natural peak flushing flows. The final column represents the volume which is the difference between the actual and the composite discharge which remains for possible depletion from the river. This analysis indicates that an average of 1,220,000 acre feet annually are required to maintain the channel substrate in the present condition. This compares with the average annual volume of 1,508,000 acre feet, leaving a surplus of 288,000 acre feet.

Minimum Streamflow Hydrograph

A minimum streamflow hydrograph has been designed to sustain the processes and conditions vital to channel morphology in the Yampa Canyon. This hydrograph was formulated on the basis that the cobble bed remain essentially free of sand during the period in July and August when spawning of the Colorado squawfish has been observed. The most sensitive subreach of the total modeled reach, an observed site of spawning, was examined after each computer simulation. This cross section at the upstream tip of the cobble bar at river mile 16.5 was permitted to be completely inundated with sand during the simulated peak. The deposited sand was then scoured off to a depth of one-half cobble below the apparent bed surface. The simulated hydrograph, therefore, allows sand deposition, but its subsequent removal maintains a sand-free cobble substrate during the months of July and August.

The shape and duration of the simulated hydrograph was dictated by the input sediment hydrograph. The 1983 measured sediment data at Mathers Hole constitutes the best available data on which to base the



AGGRADATION/DEGRADATION 1983 SIMULATED HYDROGRAPH VERSION III-4-5

Figure 31

simulated hydrograph. Since the data was measured at the initial upstream cross section in the modeled reach, no assumptions regarding travel time or sediment size distributions are necessary. The 1983 data represents one of the highest peaks and largest annual volumes on record. It was also a late runoff season. Twenty-eight percent more sand sediment was measured at Mathers Hole than the combined worst historical years on record from the upstream gaging stations. Measured data on the largest sediment discharges were collected in late June and July. These sediment discharges put the most severe demands on the system to keep the cobble bed free of sand.

The final simulated hydrograph is a minimum hydrograph required to transport the 1983 measured sediment load through the cobble reach with only minor net sand deposition. The hydrograph consists of a substantially smaller peak and volume than the 1983 hydrograph which actually delivered the sediment to Mathers Hole. It is assumed^① that measured sediment load would be delivered to Mathers Hole even with the reduced flows. It is also assumed^② that the rate at which sediment is supplied from the upstream watershed will not accelerate in the future. Since the 1983 sediment load is conveyed through the cobble reach, and since^③ no reduction in supply from the Little Snake is anticipated, it is appropriate to assume that delivery of the sediment load is possible for reduced discharges.

The simulated hydrograph has a peak flushing component for 48 hours that equals or exceeds 11,500 cfs but is less than 21,000 cfs. The natural peak discharge is recommended as a flushing discharge that will retard vegetative encroachment, replenish beach and bar areas with sand, and scour areas of sand deposition in the cobble reach. Any seasonal storage of sand in Deerlodge Park would be minimized. While flows greater than 21,000 cfs may occur, this discharge is sufficient to entrain small cobble particles, rework and maintain the cobble bars and generally insure that no major changes in the channel morphology are forthcoming. The 21,000 cfs is slightly below bankfull discharge and below the incipient motion of the median cobble diameter and should not result in any catastrophic channel change while keeping the natural processes in the channel active.

Probable Effects of Reduced Annual Flow

Prediction of the channel response to reduced flow scenarios is very subjective in the absence of knowledge regarding shape and duration of the hydrograph or upstream sediment supply. Entertaining several sweeping assumptions, however, some general river responses to reduced discharge can be postulated. Both the long- and short-term response are addressed in terms of channel morphology, vegetative encroachment, and sand deposition on cobble substrate (see Flow Chart, Figure 32).

In 1977, the lowest year of volume and peak discharge on record, approximately 450,000 acre feet flowed through the Yampa Canyon. In analyzing this hydrograph, the discharge exceeded the mean base flow of 367 cfs from March 9 to June 24, a total of 109 days. The peak discharge of 3821 cfs occurred on June 5. The discharge fell below 700 cfs on June 21 and below 100 cfs on July 4. A volume of 500,000 acre

FLOW CHART: EFFECTS OF ALTERED FLOW REGIMES ON HYDRAULIC PARAMETERS

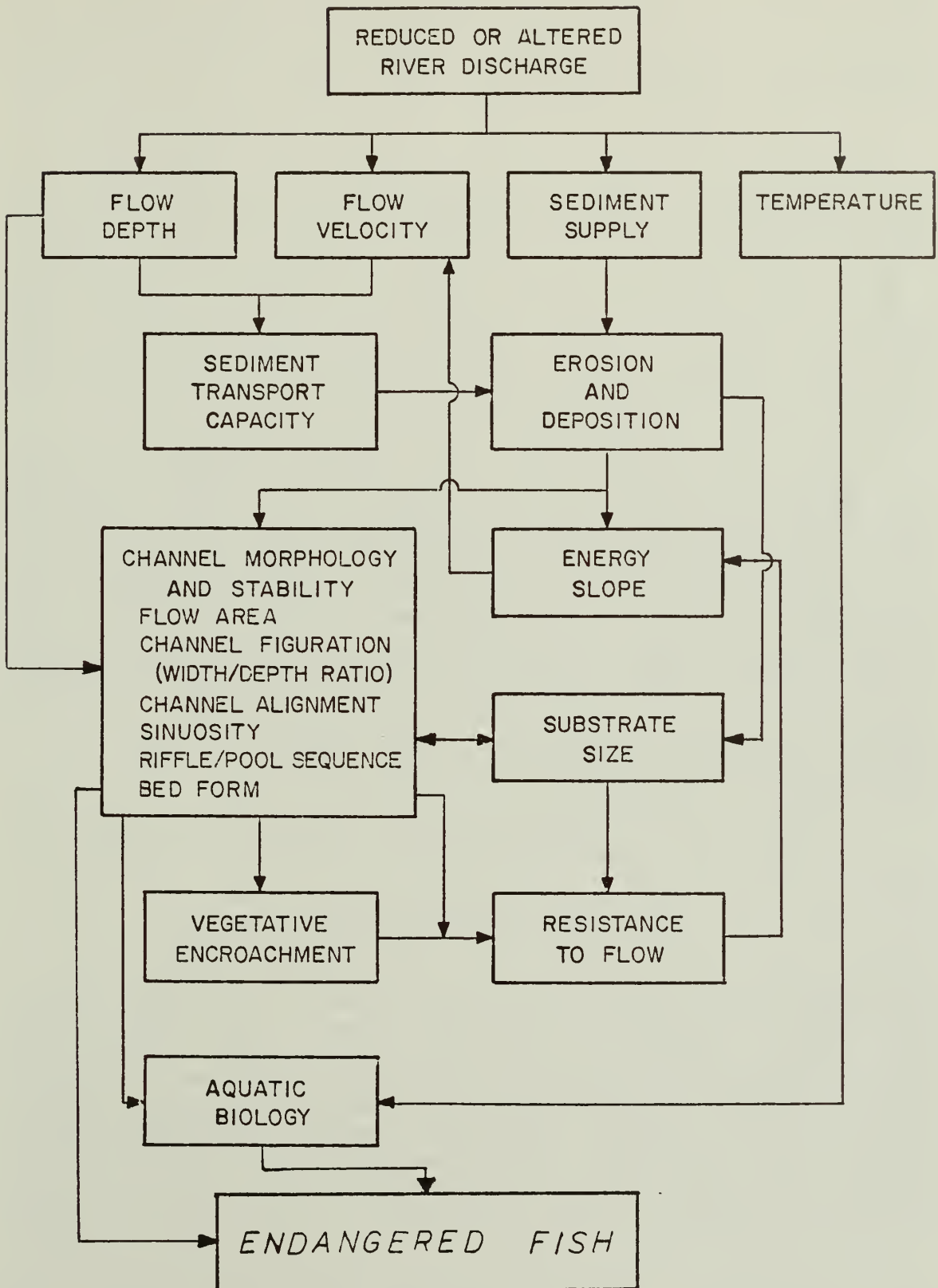


Figure 32.

feet of water is equivalent to a constant daily discharge of 700 cfs for the entire year. Comparably, a simulated hydrograph with a baseflow of 367 cfs could be formulated with a peak discharge of 11,500 cfs. If the peak of 11,500 cfs flowed for x days, then the number of days the discharge would exceed the baseflow would be given by: $21 - x$, assuming a linear rising and recessional limb.

During the short-term, one to five years, the adverse effects of a simulated hydrograph would be relatively minor. Some vegetative encroachment into the zone below bankfull discharge and on the beaches would be expected. The maximum period that the peak discharge has not exceeded 11,500 cfs is 3 years from 1959 through 1961. With a peak of 11,500 cfs for seven days, the channel should maintain its suitability as fish spawning habitat in the cobble reach. Vegetation growth on the cobble bars may be wide spread but would not effect the riparian zone below the level of 11,500 cfs. Any adverse effects could be negated by later peak discharges approaching natural conditions. Obviously, the effects of the 1977 low water year have been obliterated.

With a controlled hydrograph of a constant discharge of 700 cfs, the effects would be more pronounced. Vegetative encroachment should be extensive in this case and sand deposition in the cobble reach would occur if the sediment stored in the Deerlodge Park reach became significant. Storm events on the Little Snake drainage or in Deerlodge Park area would produce short time-to-peak hydrographs of relatively small discharges of several thousand cubic feet per second. Such events in a reduced flow scenario would be detrimental, delivering large quantities of sand to the cobble reaches, filling in the pools and possibly covering some of the cobbles. This phenomena would most likely be progressive, filling the upstream canyon pools initially. Again, the adverse impacts may be reversed by peak discharges on the order of magnitude of the natural peaks.

The long-term river response is more difficult to predict. The Deerlodge Park reach after the confluence of the Little Snake River, being an alluvial channel, is the most sensitive reach to any changes in discharge which deviate from a natural flow hydrograph. Depleted flow from Yampa River without corresponding discharge depletions from the Little Snake would generate the most severe channel response. Hydrograph shape and the temporal relationship between the Yampa and Little Snake are the key factors. Qualitatively, river channel response may include: change in flow area, stage, energy slope, channel stability, and possibly river form. Sediment loads from the Little Snake would deposit in Deerlodge Park aggrading this four mile reach of river. The bed slope would increase until the resultant hydraulic conditions could transport all of the incoming sediment supply from the Little Snake. Vegetative encroachment would ensue, stabilizing bars, reducing channel width and carrying capacity in some reaches. The river stage at higher flows would be increased and in some areas may result in overtopping the banks. In very wide sections, the change in slope may create alternate bed forms, varied flow resistance, and quite probably a more braided river than already exists at low flow. Here channel stability would be adversely effected. Overall, bed material size would decrease in this reach.

Relatively minor changes would occur in the first twenty miles of the canyon. The most severely effected areas would be beaches contiguous to the five or six pools upstream of rapids. These areas would be stabilized by vegetation growth. The upland vegetation zone would be more inaccessible in these pool areas similar to that presently existing at Big Joe Rapid. Sand beach and bar areas not stabilized by vegetative encroachment would be eroded by eddy velocities.

Some long-term channel adjustment in the cobble reach to either a constant or varied discharge should be expected. A constant discharge would effectuate a more severe response than the varied discharge. With reduced discharge, channel stability would increase, loss of channel carrying capacity would be negligible, and the effects on stage would be minor. The critical responses would be the reduction in bed material size distribution, sand deposition in the pool reaches and vegetative growth on the exposed cobble islands. Some of the cobble reaches would still be free of sand, but the majority of this reach would be lost as spawning habitat from a combination of a reduction in flow area and sand inundation of the cobble substrate. With stabilization of the channel, cobble bar evolution would cease, side channels would be closed permanently, and a single higher velocity channel would develop. The minimum stream energy required to mobilize the cobble substrate would never be exceeded. All of the dynamics of reworking the cobble islands and changing the shape and orientation of the bars would be forfeited. Water surface slope would increase above the cobble riffles and an alternating sand-cobble bed similar to the reach above Warm Springs Lake would develop. Average water temperatures in the Yampa Canyon would increase in the summer months; however, the Yampa's warming effect on the Green River would be diminished because of the reduced discharge.

The long-term effects on habitat in the cobble reach is functionally linked to the constraints imposed on sediment supply from the Little Snake and the resultant Yampa River channel response in Deerlodge Park. Storm events of uncontrolled discharge would compound the problems in the canyon by introducing large sediments loads.

CONCLUSIONS AND RECOMMENDATIONS

The minimum streamflow for natural maintenance of the stream channel morphology and related biological habitat in the Yampa Canyon encompasses a range of discharges which will transport the bulk of the total annual sediment load, inundate the active channel area, maintain existing substrate characteristics and sustain the dynamic processes forming the integral features of the channel. Based on the results, the required minimum streamflow is defined by a hydrograph, whose components include baseflow, rising and recessional limbs, and a peak discharge. The minimum streamflow hydrograph, considered critical for channel stability was determined using widely accepted sediment transport and hydraulic principals.

To define the channel hydraulic morphological conditions at river mile 16.5 and 18.5, the results of the USFWS and NPS studies were combined. Field data collected for the application of the PHABSIM

computer model was used in the water and sediment routing analysis to develop the minimum streamflow hydrograph. This data was presented to the USFWS in October, 1983 fulfilling the first objective of this study.

The second objective, to describe the channel morphology in the cobble substrate reach, was accomplished through a discussion of riffle-pool sequence evolution, cobble particle mobilization, and sand transport over the cobble substrate. This discussion was supplemented with a description of the site's physical and geological features. The uniqueness of the reach is defined by the uniformity of the substrate size in the riffles, the irregular spacing of the riffle-pool sequence, and the sand transport characteristics of the riffle-pool subreaches.

Geomorphically, the sites at river mile 16.5 and 18.5 have some similar characteristics. Both sites have a cobble bar which separate the flow into two or more riffle channels. The cobble bars are depositional features of floods at flow expansions. Sand substrate pools are located upstream of the bars where the channel is constricted. The pools are relatively deep with a water surface controlled by the riffle backwater.

Hydraulically, the two sites have several dissimilar characteristics. River mile 18.5 has a more pronounced thalweg contiguous to the cobble bar which results in larger substrate. The flow diversion around the bar is not as fully developed. Being a smaller channel there is less diversity of substrate in the immediate channel around the cobble bar than at river mile 16.5. The cobble bar at RM 16.5 is more dynamic, the flow attacking the talus slopes and the bar vertically accreting at faster rate. This cobble bar is less submerged at high flows.

All the sediment transported in the cobble reach is considered as throughput or washload. Except for flows near bankfull discharge, virtually all the transported sediment is sand size particles and smaller. Small gravels are transported as bedload at discharges less than bankfull. This a minute portion of the total load. Near bankfull discharge, small and medium cobbles are moving as bedload. Again, this represents a infinitesimal part of the total load. Although the transported sediment load is large, the river maintains a consistent substrate through a range of flows. Changes in substrate are experienced at peak flows. Sand substrate pools are scoured to cobble or bedrock base at the peak and are refilled with sand on the falling limb. Some channel areas, outside the thalweg, are subject to sand deposition at peak flows as a function of the large transported load.

The range of discharges required to preserve these morphological conditions during the summer months of July and August have been determined through a mathematical simulation of the hydraulic and sediment transport processes. The results of the simulation are based on the 1983 sediment data measured at Mathers Hole. The range of discharges for channel maintenance is presented in the form of a seasonal discharge hydrograph.

The physical model study revealed that sand can be scoured from cobble substrate to a depth of one average cobble diameter without cobble mobilization. This scour depth will be less when sizes larger

than sand are trapped in the interstices. In the field the cobbles are free of sand to a depth of one-half cobble diameter below the mean cobble surface. The minimum stream flow hydrograph was designed to insure that the cobble bed was free of sand to depth of one-half cobble diameter from July 11 to August 15.

Two recommendations for future study are: a controlled study of Colorado squawfish spawning substrate preference and comparison of hydraulic and substrate characteristics of observed spawning areas in other rivers. The first study could be performed in laboratory flume with a variety of substrates. The second study would involve an inventory of hydraulic substrate, and channel morphological characteristics.

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APPENDIX A

PHYSICAL MODEL STUDY

Range of Simulated Conditions

The primary objective of the flume study was to identify the important processes and flow conditions for which sand is transported over, deposited on and scoured from a cobble substrate. A second objective was to calibrate the collection efficiency of the Helley-Smith bedload sampler on a cobble substrate.

The physical model study was based on hydraulic and substrate conditions of the cobble bar at river mile 16.5. This cobble bar functions as spawning habitat for the endangered Colorado squawfish. Hydraulic data gathered on this reach during the summer of 1983 has been used to establish the simulated conditions for the flume study. The data collected included cross sectional profiles, velocities, water surface slopes and surface and subsurface substrate particle sizes.

Consultation with biologists assisted in finalizing the range of hydraulic conditions to be modeled in the flume study. A sand-free cobble substrate is the preferred spawning habitat of the squawfish during the months of July and early August. The modeling parameters were determined from field data collected during the spawning period at moderate to low discharges (generally 500 to 4000 cfs). Depth (1-4 feet), velocity (1-5 fps) and slope were simulated in the flume on a one to one modeling ratio of prototype to model.

Laboratory Facilities

The facilities used in this flume study are located in the hydraulic lab at CSU Engineering Research Center. A 8' x 4' x 200' water and sediment recirculating flume was used in this study. The flume has a variable slope which covers the range the field conditions to be simulated. Three pumps, which can be operated independently, supplied water at a maximum rate of 98 cfs.

The flume was divided into three sections; a roughness section, a test section, and a sediment collection section. Boulders were permanently fixed to first 100 feet of flume bed to insure fully developed turbulent flow prior to the test section. The test section length was fifty feet. Clean cobbles (62 mm median diameter) from the Poudre River were uniformly distributed on the flume bed to a depth of seven to nine inches (approximately three times the cobble median diameter). The remaining fifty feet of flume were used to store excess fine sediment not recirculated in the system.

Sand was introduced to the system just upstream of the test section. A vibrating sand feeder, located on a stationary platform on top of the flume, supplied sand at varying controlled rates. To uniformly distribute the sand across the channel a shield was mounted beneath the feeder.

A sediment trap was constructed at the end of the test section to collect all the coarse sand moving as bedload over and through the cobbles. The trap consisted of trough (parallel boards) about one foot wide and $3/4$ foot deep oriented 45 degrees to the flow direction. Inside the walls of the trough, a PVC pipe with a narrow lengthwise slit, was installed. Sheet metal covered the trough and directed sediment into the narrow slot in the pipe. The upstream end of PVC slotted pipe was connected to pumping system that siphoned water out of the flume and into the slotted pipe. A sediment tank was connected to the downstream end of the PVC slotted pipe. In this manner water was circulated continuously through the slotted pipe washing any captured bedload particles into the sediment tank underneath the flume. The tank plumbing was valved to bypass the circulating water and sediment when a sample was not being collected.

Data Collection

In all phases of the flume study the following hydraulic data were collected: water discharge, mean velocity, depth, water surface slope, and flume bed slope. Water discharge was monitored by manometers attached to the pipe system of the pumps. The flow depth and slope was also measured using a manometer. The average center channel velocity was measured at the 0.6 depth below the water surface with a Price pygmy meter. To check the assumption of a logarithmic velocity distribution, several vertical velocity profiles were measured at various points in the channel. The flume bed slope was surveyed.

The total bedload sediment transport was collected using the trap and storage tank system. During the sampling period coarse bedload accumulated in the tank and suspended fine material was ejected with excess water. Increases in the stored sediment were monitored with a point gage. The tank was constructed with plexiglass window to view the sediment as it was deposited. After a sampling run, the sediment was allowed to settle, the bed was leveled and the depth of sediment was measured. The bedload transport was calculated by timing the period of flow to the tank.

To calibrate the Helley-Smith bedload sampler for coarse size sediment moving over a cobble bed, the sampler was operated within ten feet of the trap. The sampler was suspended from a mobile platform and lowered to the bed, resting in midflume for 30 second intervals. Upon raising the sampler the 250 micron mesh collection bag was emptied through the three inch square nozzle into a bucket by flushing it with a hose. Two sets of Helley-Smith samples were collected for each run.

The Helley-Smith technique used in the flume study was the same as that employed in the field. For the purposes of this study the bedload transport rate measured by the trap and tank system is considered the actual bedload transport rate and the Helley-Smith sample is the measured transport rate.

There were three phases in the flume study. The purpose of the first phase is to compare the sampling efficiency of the Helley-Smith bedload sampler on a cobble bed for the desired range of hydraulic conditions. In this phase all hydraulic and sediment data was collected on each run. The first phase consisted of 70 flume runs.

In second phase, the efficiency of the Helley-Smith sampler was calibrated for a range of hydraulic conditions over a sand bed. Again, both hydraulic and sediment data was collected on each run. There was a total of ten flume runs in the second phase.

Scouring processes in a cobble bed inundated with sand were investigated in the third phase. Hydraulic data and Helley-Smith bedload samples were collected for each run. Flow velocities were recorded at two points in the test section. Additionally, the scour of sand from the cobble bed was recorded from observation through the plexiglass side wall. There was a total of eleven flume runs in the third phase.

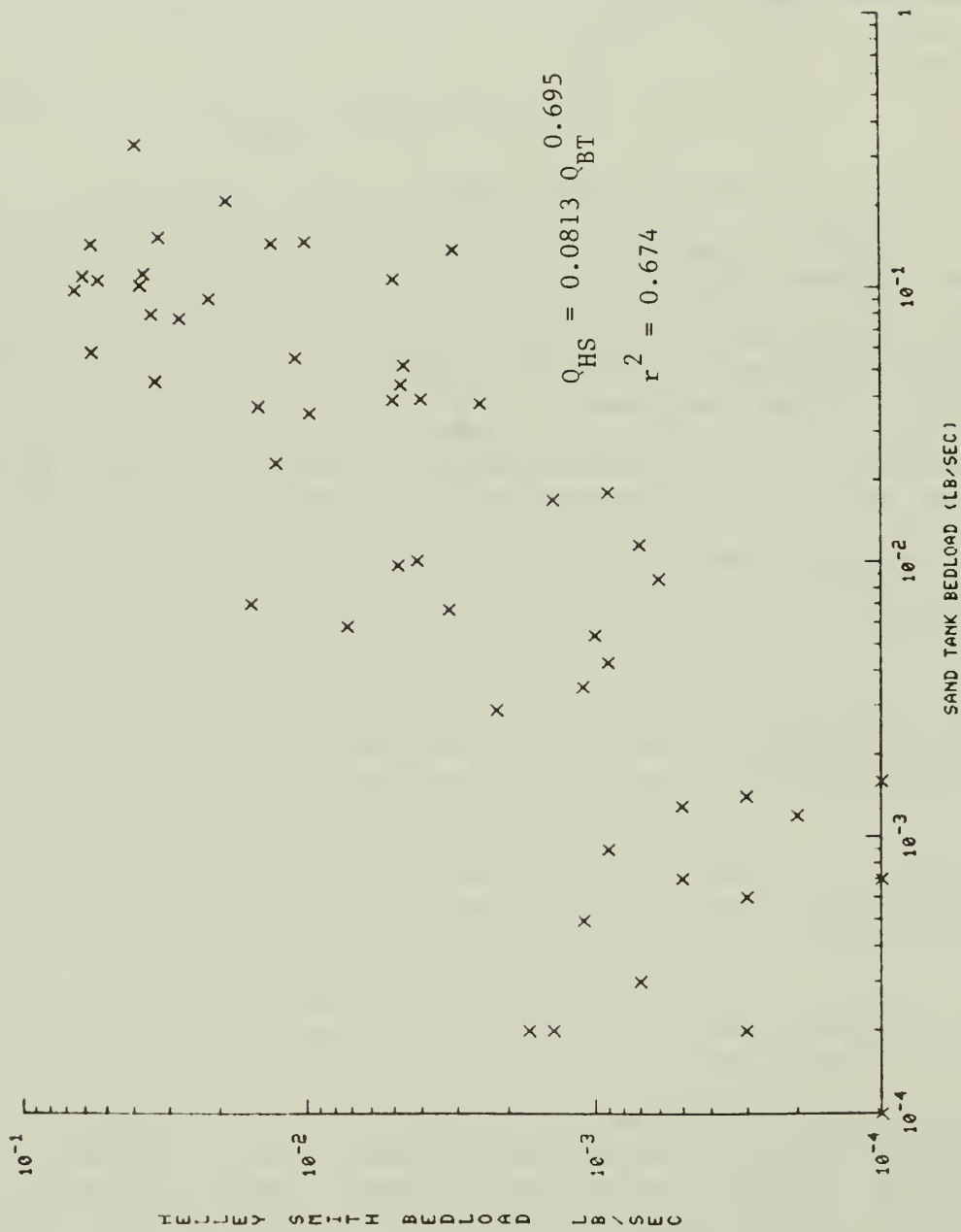
Calibration of the Helley-Smith Sampler

Sand was introduced to the cobble substrate at the upstream limit of the test section. Initially, the sand accumulated directly below the feeder. Once the bed aggraded to a height of approximately the relative roughness of the cobbles, it began moving as bedload into the test section. The sand inundation of the forty foot cobble test section occurred in the form of a progressive wave. Although some finer sand drifted over and deposited in the bed preceding the coarser sand wave, these quantities were very minor.

Seventy-two sets of two bedload measurements per discharge were made with the Helley-Smith sampler in the flume. The experiments were designed to measure bedload over a range of velocity, depth, and sediment transport conditions. Only sediment moving as bedload was considered in the analysis. Some sediment was transported in suspension but hydraulic conditions limited this load to the smaller size fractions.

The Helley-Smith load (measured bedload) was divided into size fractions and was compared with the bedload captured in the sediment trap (actual bedload). The results show very large scatter in the data (Figure 33). For the larger size classes the actual bedload exceeded the measured bedload in 84% of the runs. Conversely, for finer sediment sizes greater quantities were measured with the Helley-Smith sampler. The sediment trap was less effective in capturing the smaller size fractions which may have passed over trap opening in suspension.

The coarser size bedload moved around and through the cobbles below the apparent bed surface defined by the average height of the cobbles. In this manner, the sand can sneak under the sampler, but still be collected in the trap. As result, the actual bedload will be consistently greater than the bedload measured in the sampler. It was observed that the Helley-Smith load is sensitive to local conditions on the bed with respect to relative roughness, nozzle orientation, and proximity to the sand level in the cobble bed. Often a sand string or wave will pass by the sampler distorting the bedload transport measurements. The sampler was observed to dramatically oversample when placed on a sand bed. It collected large quantities of sand even when no sand was moving into the sediment trap.



HELLEY-SMITH US. SAND TANK FOR PARTICLE SIZE 0.00338 FT.

Figure 33

On a uniform cobble substrate, Helley-Smith measurements result in underprediction of the actual bedload transport. Irregularity of the bed, both in terms of substrate and relative roughness, improves the reliability of using the sampler in the field. The diversity of substrate permits a wide range of sampling conditions which results in better correlation of bedload with discharge. The Helley-Smith under-samples the coarse material whenever the sampler does not rest directly on the bedload contact surface.

APPENDIX B

MATHEMATICAL MODEL DESCRIPTION

Sediment Transport Processes

A river channel responds with either sediment deposition or scour depending on its ability to move sediment (transport capacity) and the quantity of sediment supplied from upstream sources. When the transport capacity of the river reach exceeds the upstream supply, the flow will remove sediment from the channel bed and banks, expending excess energy in the process. Conversely, if the supply exceeds the capacity, aggradation will change the bed substrate. For the same flow conditions, smaller sediment particles will be transported at larger rates than large particles. Sediment transport capacity, therefore, is best formulated as a function of size fraction of the sediment.

The sediment transport capacity of the bed material load is a combination of two processes, bedload and suspended load. The sediment which moves by the phenomena of rolling or creeping in contact with the stream bed is referred to as bedload. The suspended load consists of sediment particles which are suspended or saltated into the main zone of flow. The bed material load is the summation of the two types of processes. Turbulent mixing and gravity results in a continuous interaction of particles between the bed and the stream flow. Suspended load particles which are not found in appreciable quantities in the bed, are referred to as wash load.

The bed load transport capacity was calculated using the Meyer-Peter and Müller formula. Bed load transport is computed as a function of an exceedance of threshold stream power. This equation is particularly appropriate for channel armoring processes and for streams with a large range of sediment sizes. This is a typical value used for sand size material from the Shield's diagram. In the Meyer-Peter and Müller equation the dimensionless critical shear stress for sand size material is 0.047.

Suspended transport capacity is based on a technique developed by H. A. Einstein which is widely accepted and universally applied. This method integrates a sediment concentration profile as a function of the depth of flow. The bedload layer, as calculated using the Meyer-Peter and Müller formula, is a point of known concentration from which the entire concentration profile may be determined. Turbulent transport theory is the basis for determining the concentration profile shape.

Model Assumptions

Several assumptions are embodied in applying the computer model to the Yampa River. The broadest assumption is the use of the sediment transport models for predicting capacity in a cobble bed stream. Most models have been developed for sediment in alluvial sand bed streams where an infinite supply of sediment is available from the bed. Through the use of the Meyer-Peter and Müller equation and the routing of sediment by size fractions it is possible to predict the phenomena of

armoring. The coarsening of the bed surface material through the armoring process limits the availability of the finer subsurface material, and the capacity will exceed the supply.

It is not clear how stream capacity may deviate from theory when the original bed is cobbles. Meyer-Peter and Müller had used gravels and coarse sand to derive their bedload equation. The accuracy of this method will be limited by the correct choice of the critical shear stress parameter in the formula. The critical shear stress parameter was chosen to be 0.047 because most of the sediment load is sand washing through the system. This method of combining bedload and suspended load models represents the best available technology for the prediction of sand transport capacity.

A second major assumption involves the uniform distribution of sediment deposition or scour laterally and longitudinally in the channel. Sediment transport characteristics in each reach are a function of the average hydraulic conditions in the channel. Localized scour and deposition are not reflected by the model.

Hydraulic conditions are assumed to be subcritical and the discharge constant for a given time step. The HEC-2 calculations assume a rigid boundary condition, however, the cross section stations are modified at each time step. The following assumptions are inherent in HEC-2 water surface profile model:

- i) The flow is steady and gradually varied.
- ii) Hydrostatic pressure distribution exists everywhere in the channel.
- iii) The flow is one-dimensional.
- iv) The total energy head is equal everywhere in the channel.
- v) The channel bed slope is mild.
- vi) The channel roughness varies little with stage.

Channel roughness does vary with discharge, it is a limitation of the model not to accommodate changes in roughness values. This limitation will affect the stage at lower flows; however, since the channel configuration is not appreciably modified by aggradation/degradation, the overall affect on sediment transport is assumed to be minor.

The initial channel surface and subsurface bed material for each subreach is represented by a size distribution. Variation of substrate across the channel is neglected. The thickness of the surface and subsurface bed material is specified at the outset of the modeling exercise and is assumed to be of uniform thickness throughout the reach. When the surface layer has been removed, the size distribution reflects the availability of particles from the subsurface material.

Model Calibration

The water component of the model, specifically the HEC2 water surface profile, is calibrated from a knowledge of the peak water surface elevations at each of the eleven cross sections. Since a stage-discharge relationship has been established at Mathers Hole, the channel roughness can be adjusted to give a good estimate of water surface at each cross section and an exact elevation at Mathers Hole, the final upstream cross section.

From observations and cross sections measurements, minor amounts of aggradation and degradation were noted during the 1983 field season. Some small amounts of sand were deposited during the peak discharges. The model was calibrated with the 1983 measured data. The predicted river response was observed in the field; aggradation at Mathers Hole during the peak, degradation of the sand substrate cross section, and general hysteresis loop of deposition and scour.

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